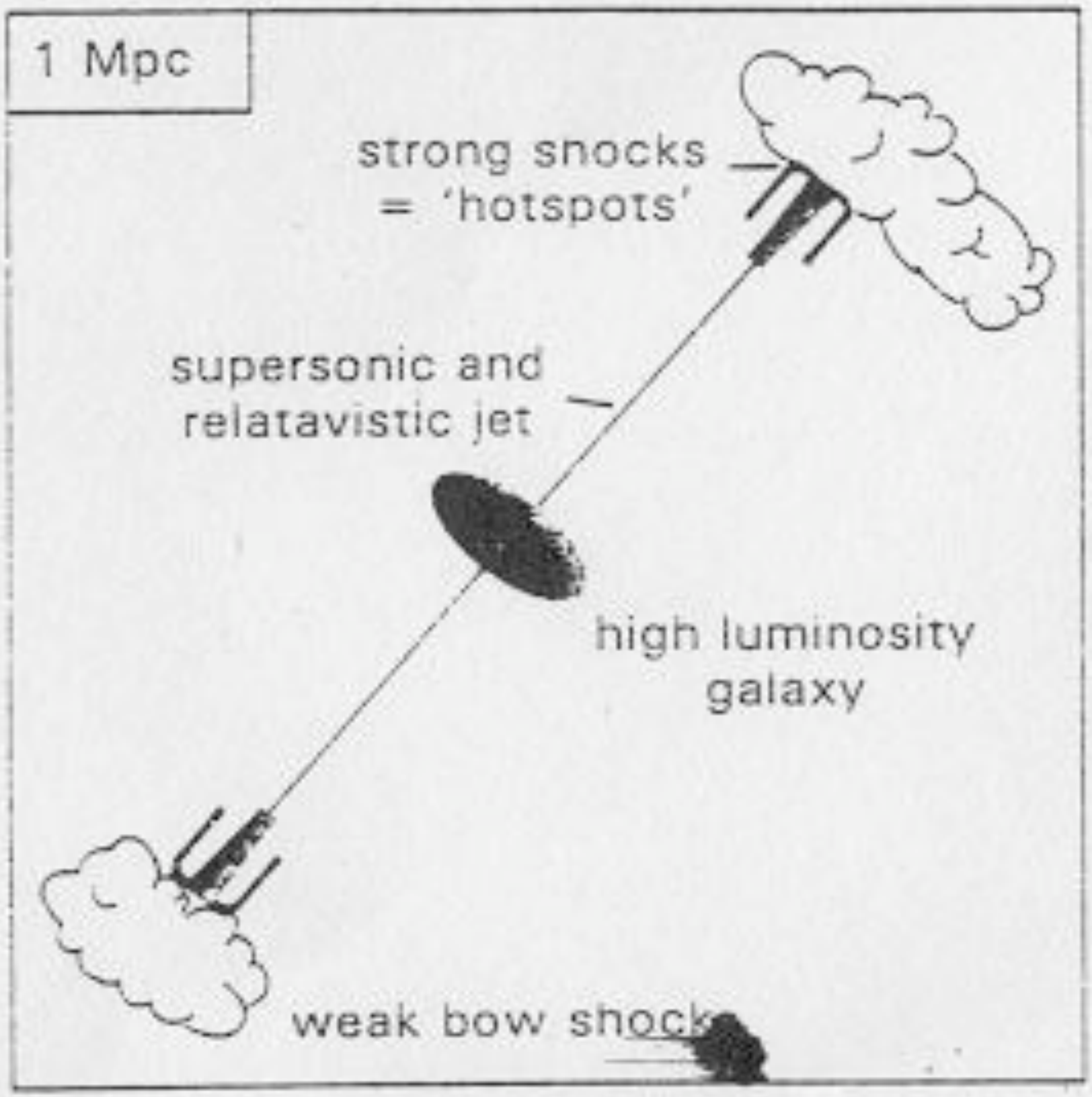
AGN 2

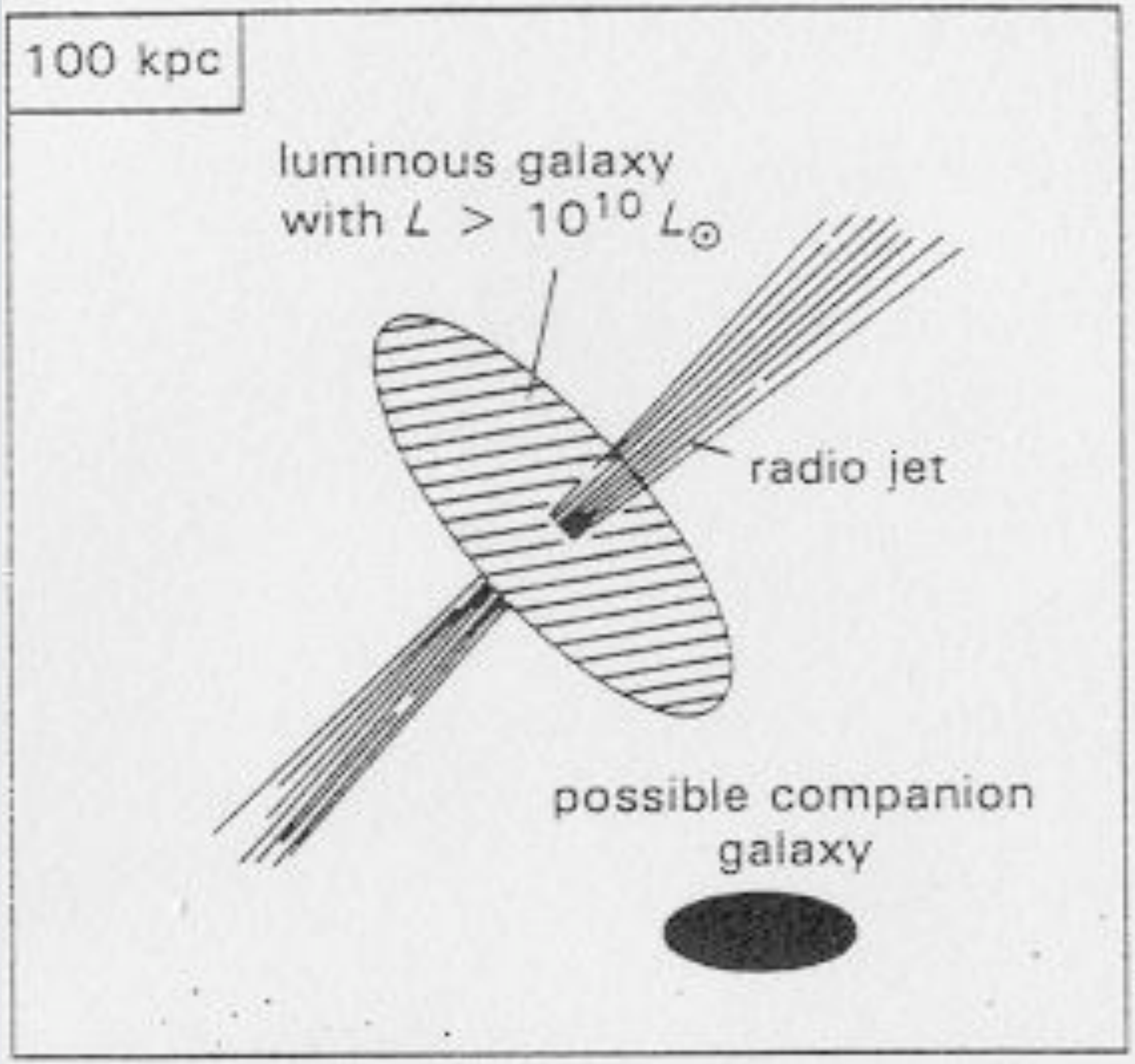
CHANDRA X-RAY OBSERVATORY

AGN at different scales from 1 Mpc to 10^{-4} pc

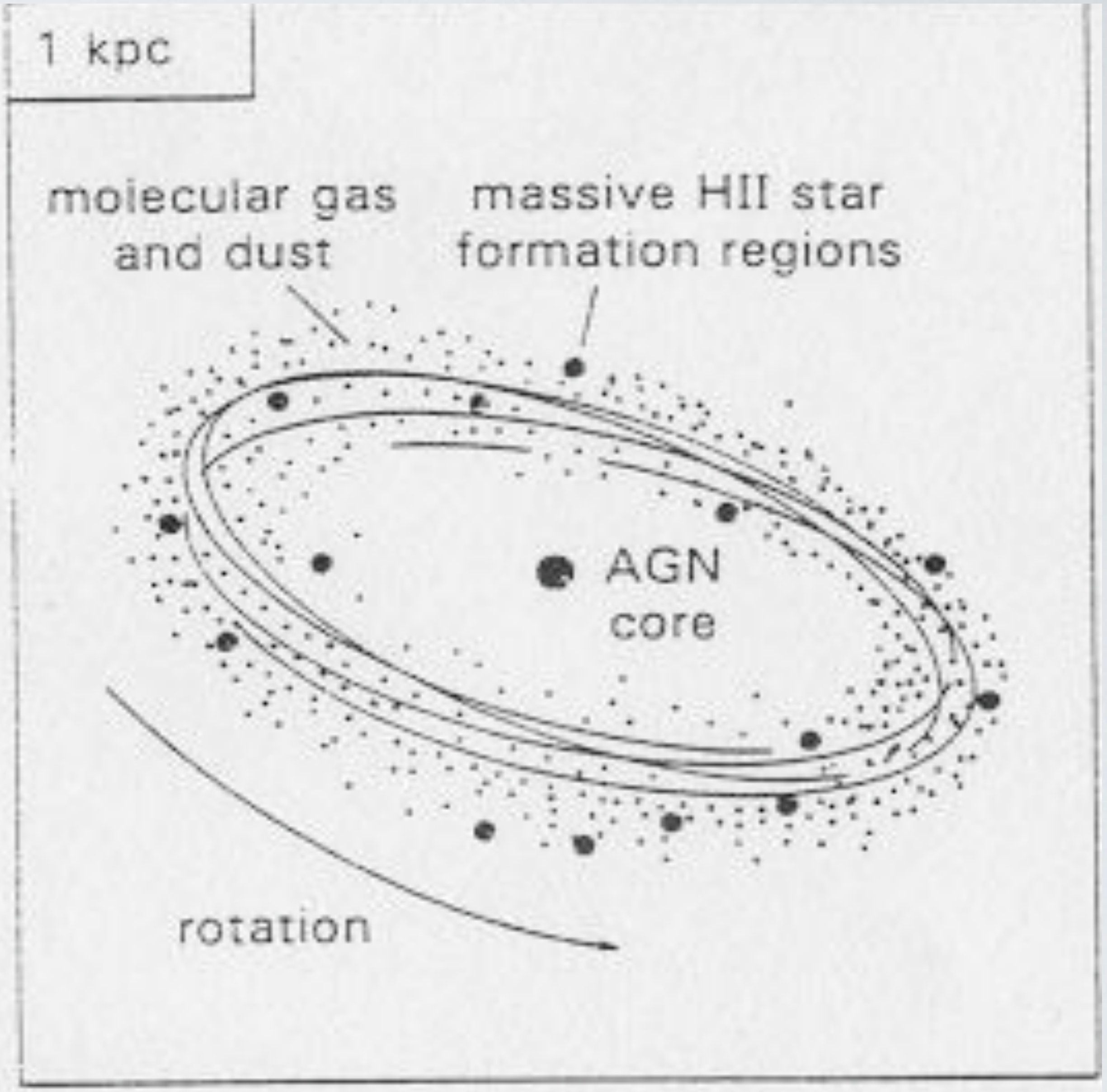


Extended radio sources — shown is an FRII source with an edge-brightened structure. The FRIs have lower jet velocities and fade-out to the ends.

AGN at different scales from 1 Mpc to 10^{-4} pc

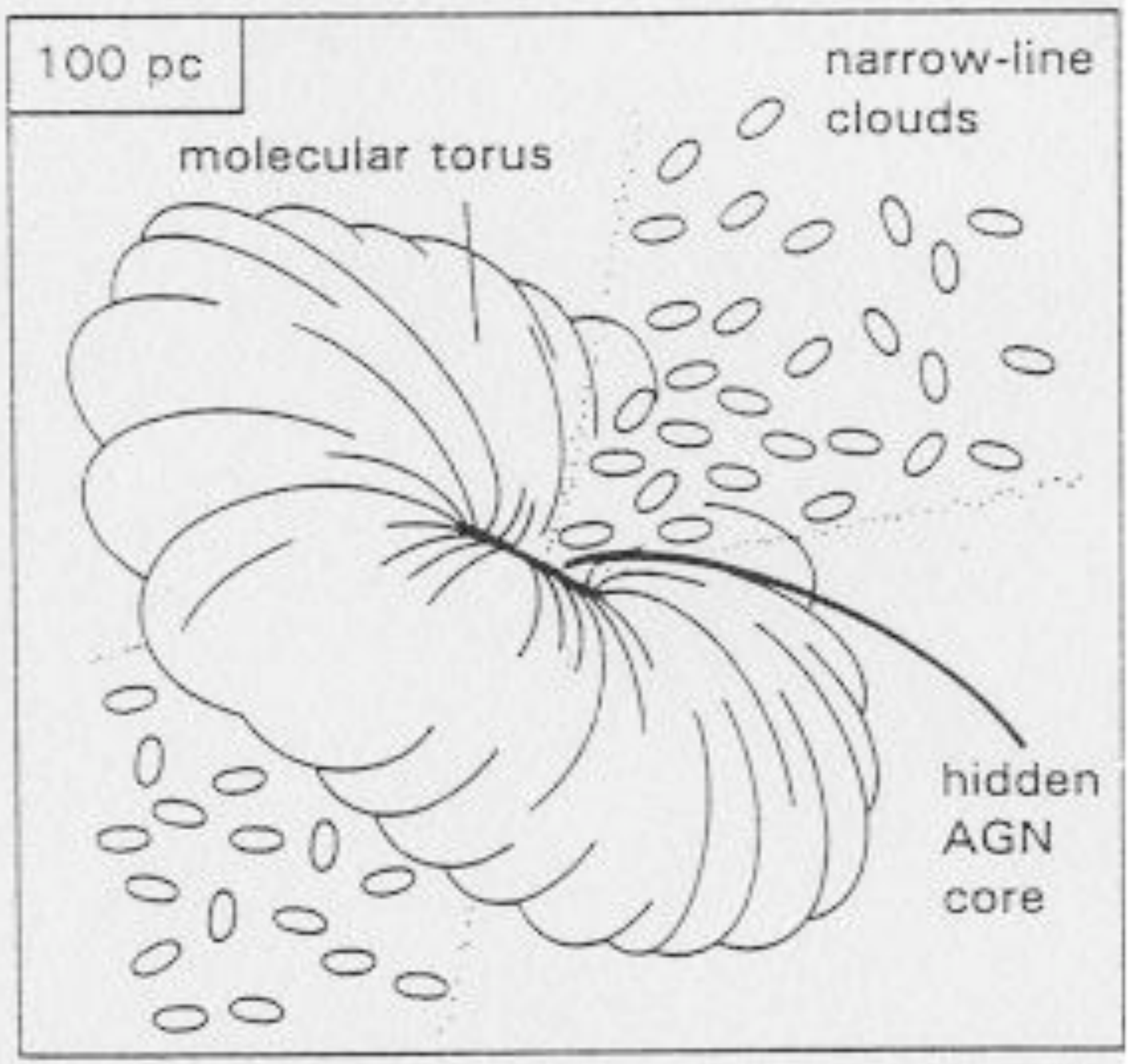


The host galaxy. Although shown as an early type galaxy with a smooth profile, it could also be highly irregular with multiple nuclei as a result of merging.

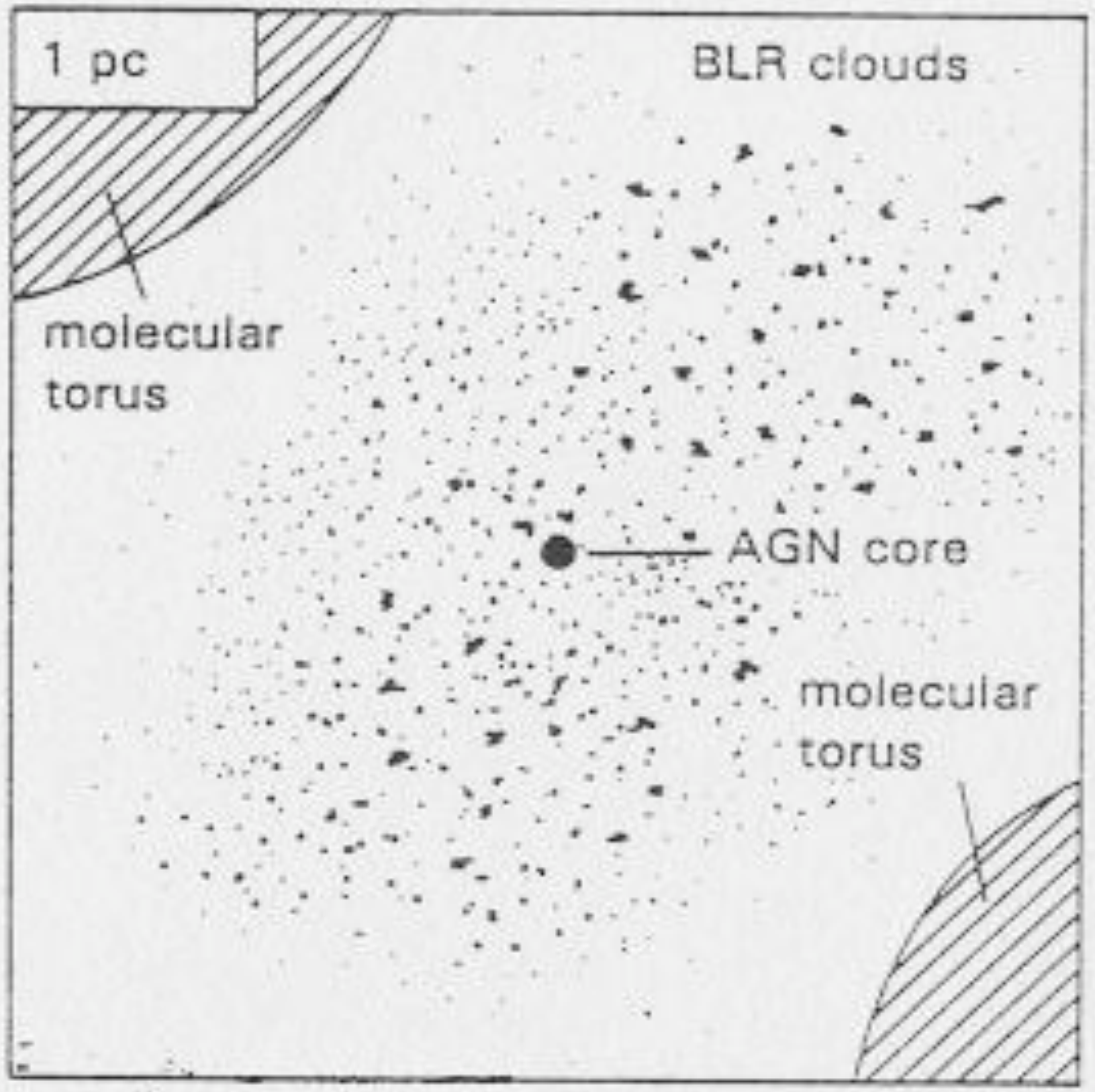


The central kpc star formation disk. This strong far infrared emitting zone might be fed by a bar structure, as seems to be the case for NGC1068.

AGN at different scales from 1 Mpc to 10^{-4} pc

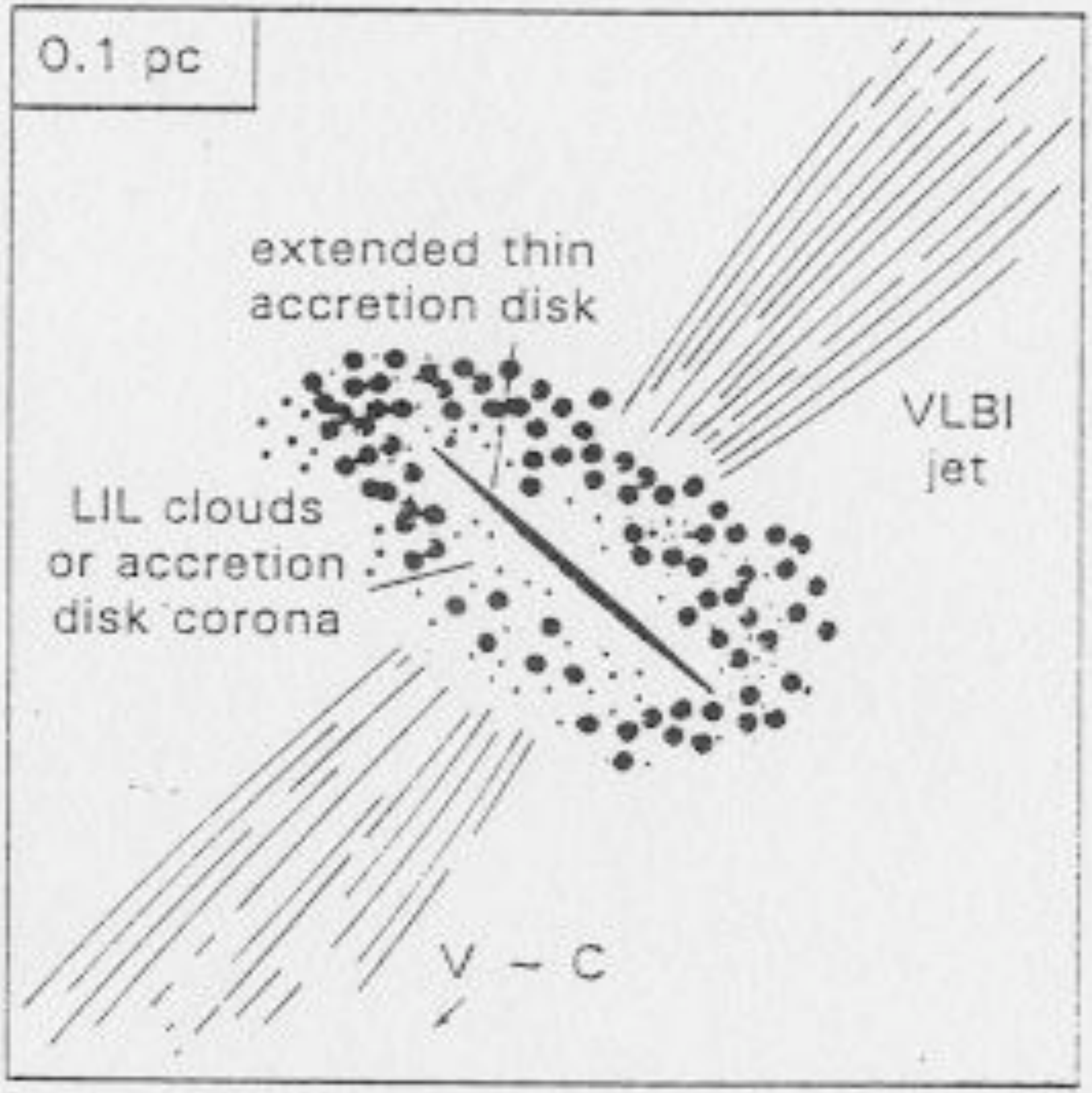


The narrow-line region comprising small but numerous clouds of the interstellar medium ionized by the central AGN core.

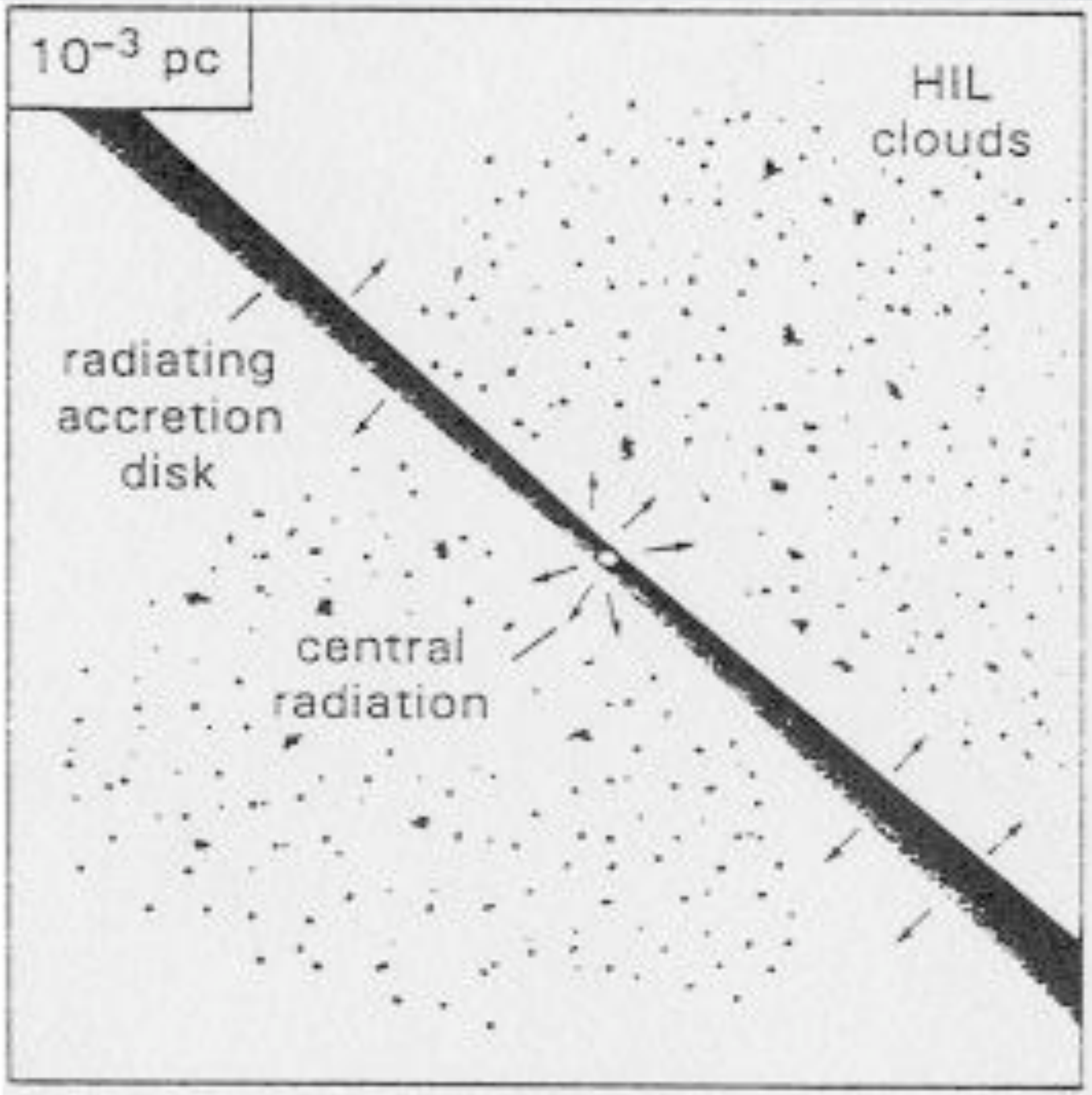


The outer extent of the broad-line region and the deep-walled molecular torus which can provide an effective shield of the central AGN, depending on the relative orientation of the observer.

AGN at different scales from 1 Mpc to 10^{-4} pc

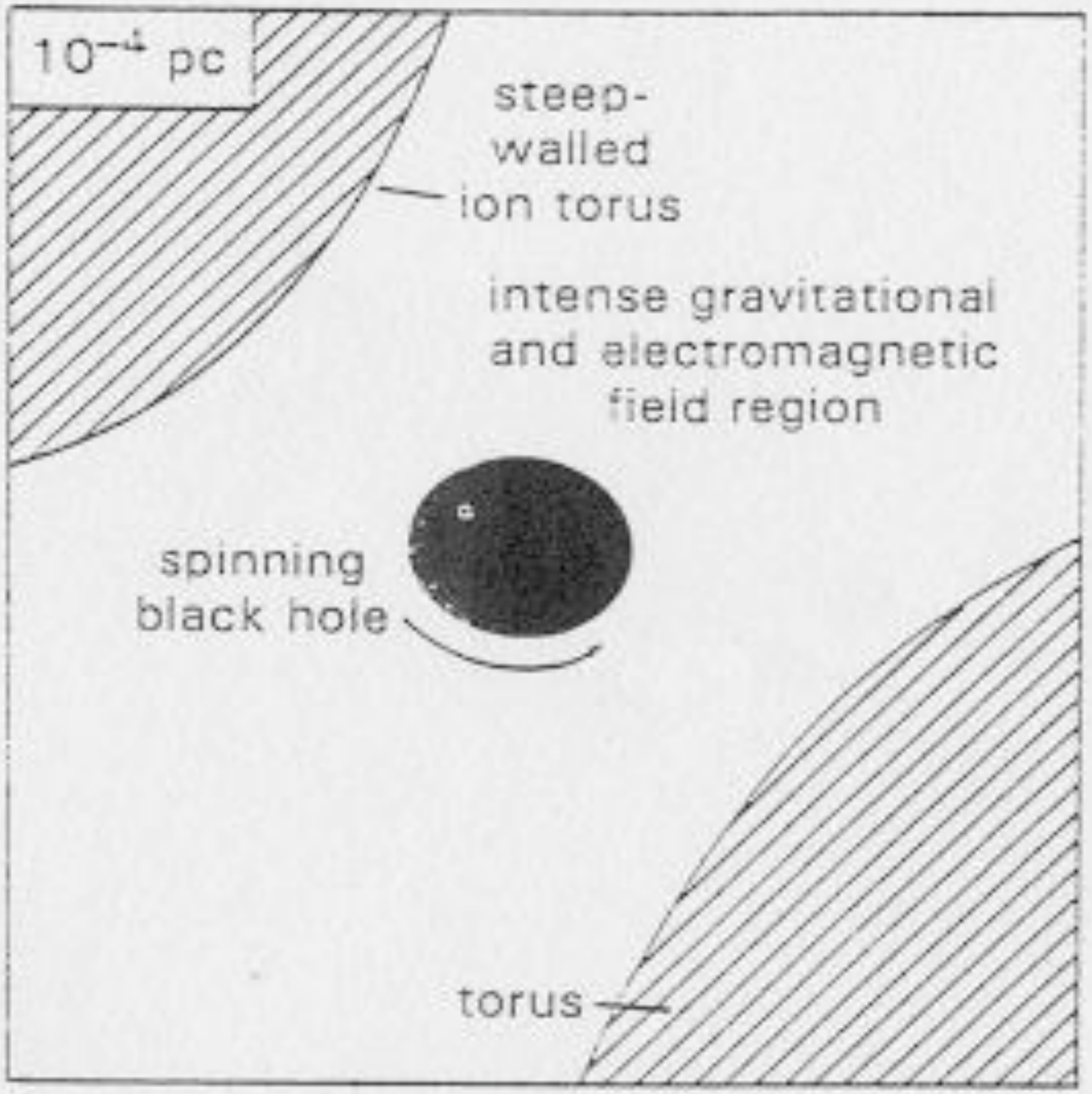


Inside the molecular torus — the VLBI jet becomes self-absorbed closer in. and the low ionization lines of the BLR. which might be the corona of the accretion disk.



The accretion disk which radiates strongly at UV and optical wavelengths. The high ionization clouds of the BLR are excited by the central continuum radiation field.

AGN at different scales from 1 Mpc to 10^{-4} pc



The black hole. The Schwarzschild radius for a 10^8 $M_\odot$ black hole is 2 AU (10^{-5} pc). The spin will introduce twisted magnetic field lines and particle acceleration.

Accretion disk

- Geometrically thin, optically thick accretion disks

$$T(r) = 6.3 \cdot 10^5\,\mathrm{K} \left(\frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}}\right)^{1/4} \left(\frac{M_{\mathrm{BH}}}{10^8 M_\odot}\right)^{-1/4} \left(\frac{r}{R_{\mathrm{S}}}\right)^{-3/4}$$

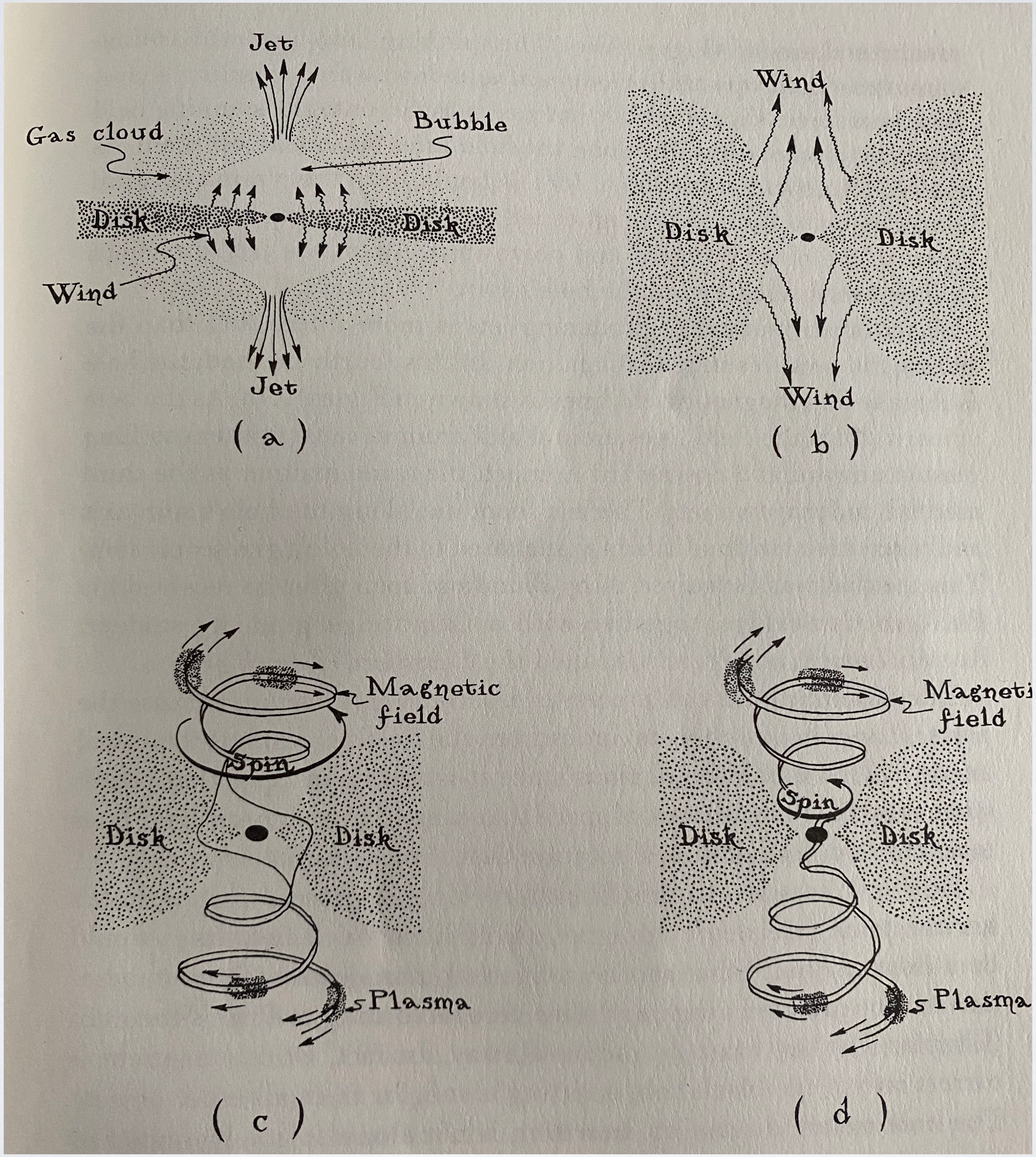
- Inflow due to viscosity, but:

$$\mathrm{Re} \sim 3 \cdot 10^{13} \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{R}{1\mathrm{pc}}\right)^{1/2} \left(\frac{n}{\mathrm{cm}^{-3}}\right) \left(\frac{T}{\mathrm{K}}\right)^{-5/2}$$

- must be *turbulent viscosity,* proportional to $l_{turb}\ v_{turb}$

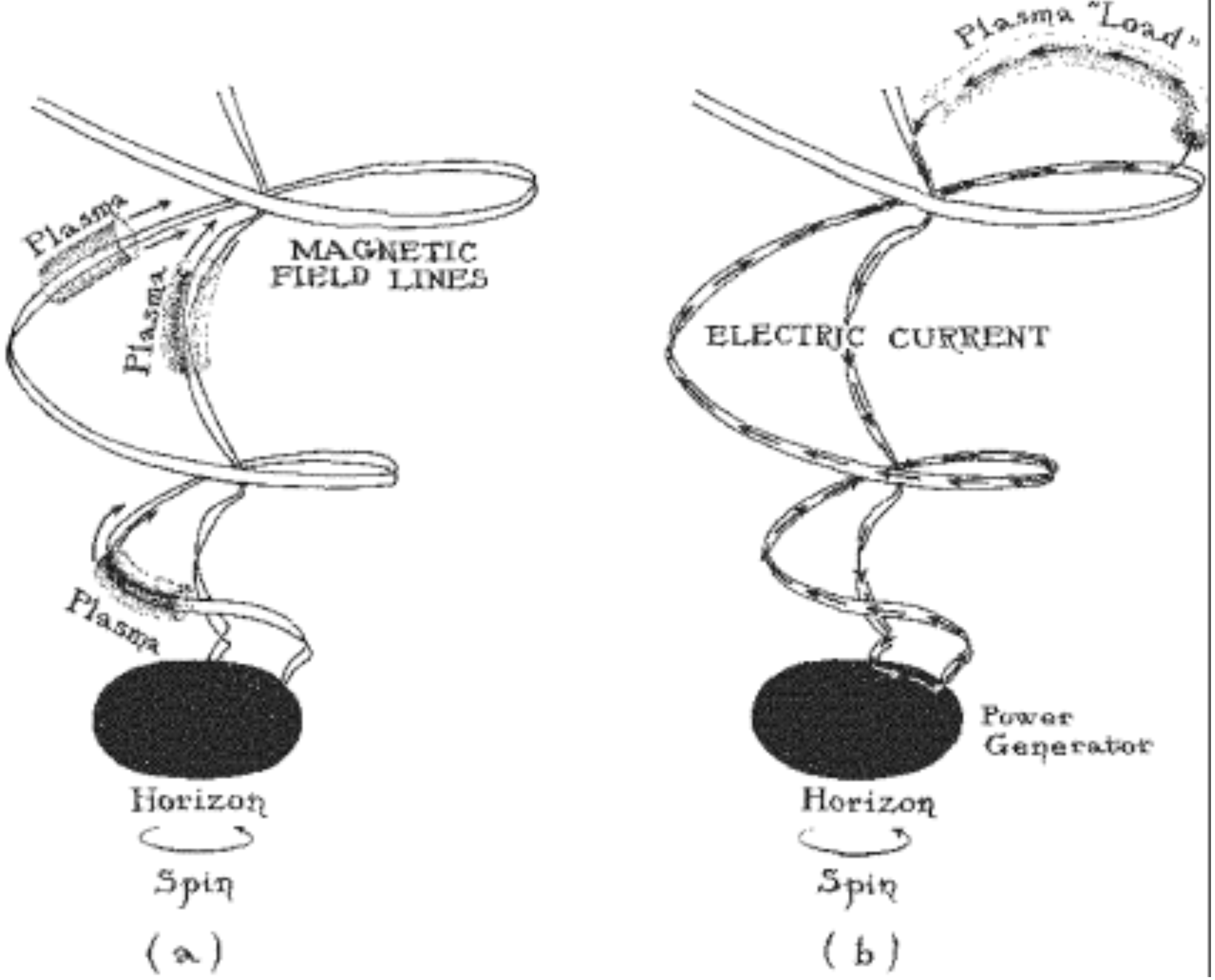
- Geometrically thick optically thin models, where radiation is advected into the black hole (radiative efficiency is small)

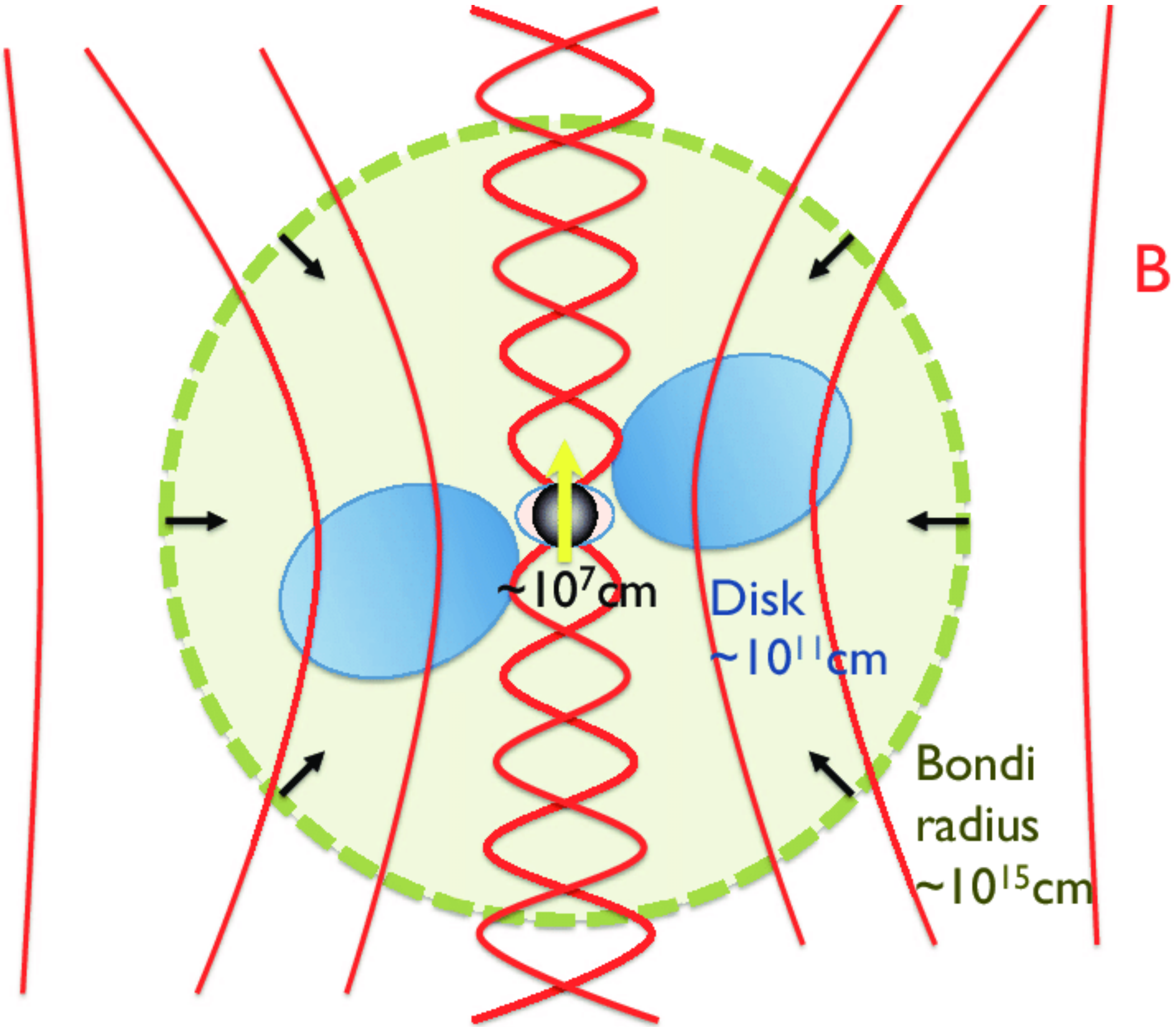
Formation of jets

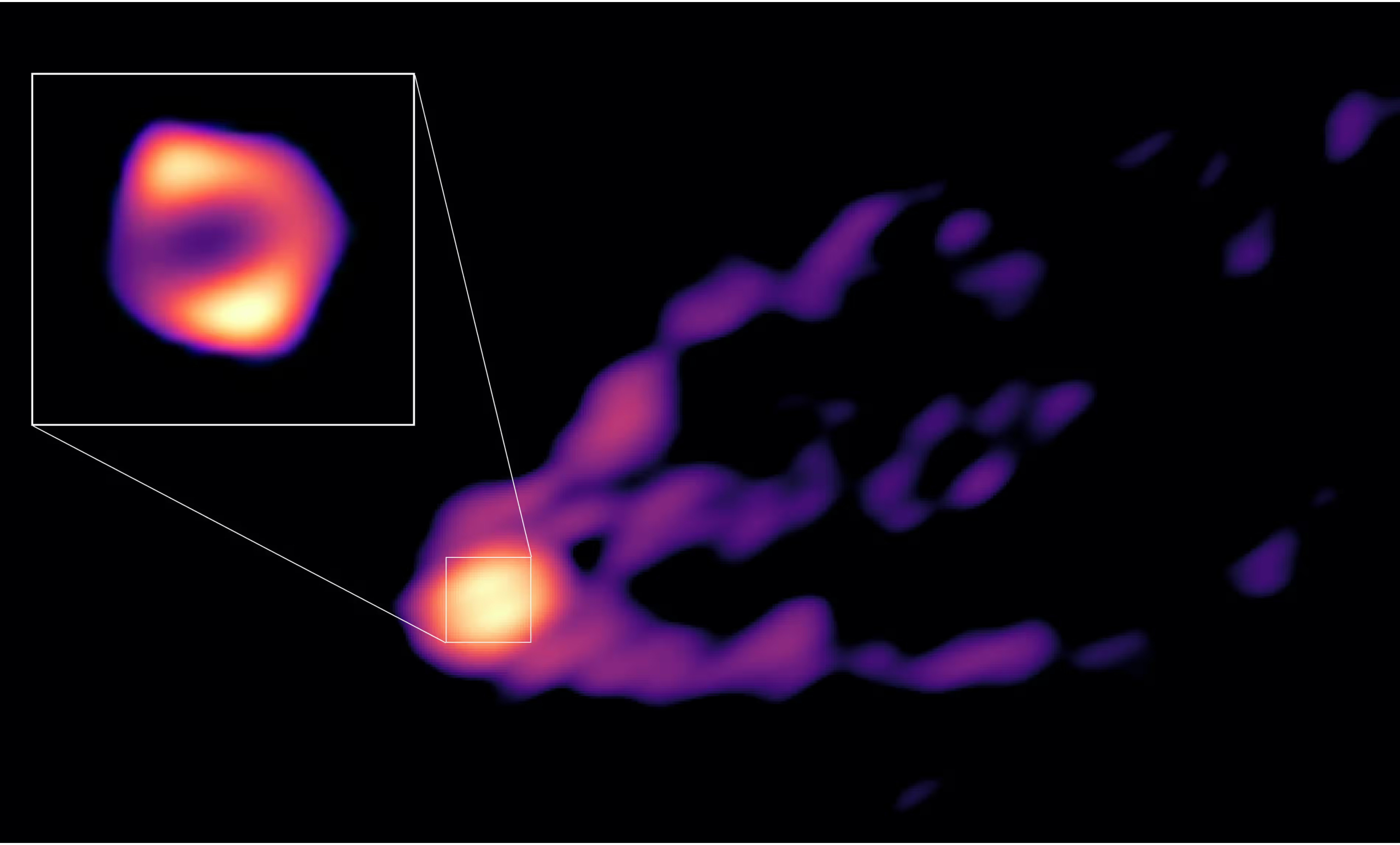


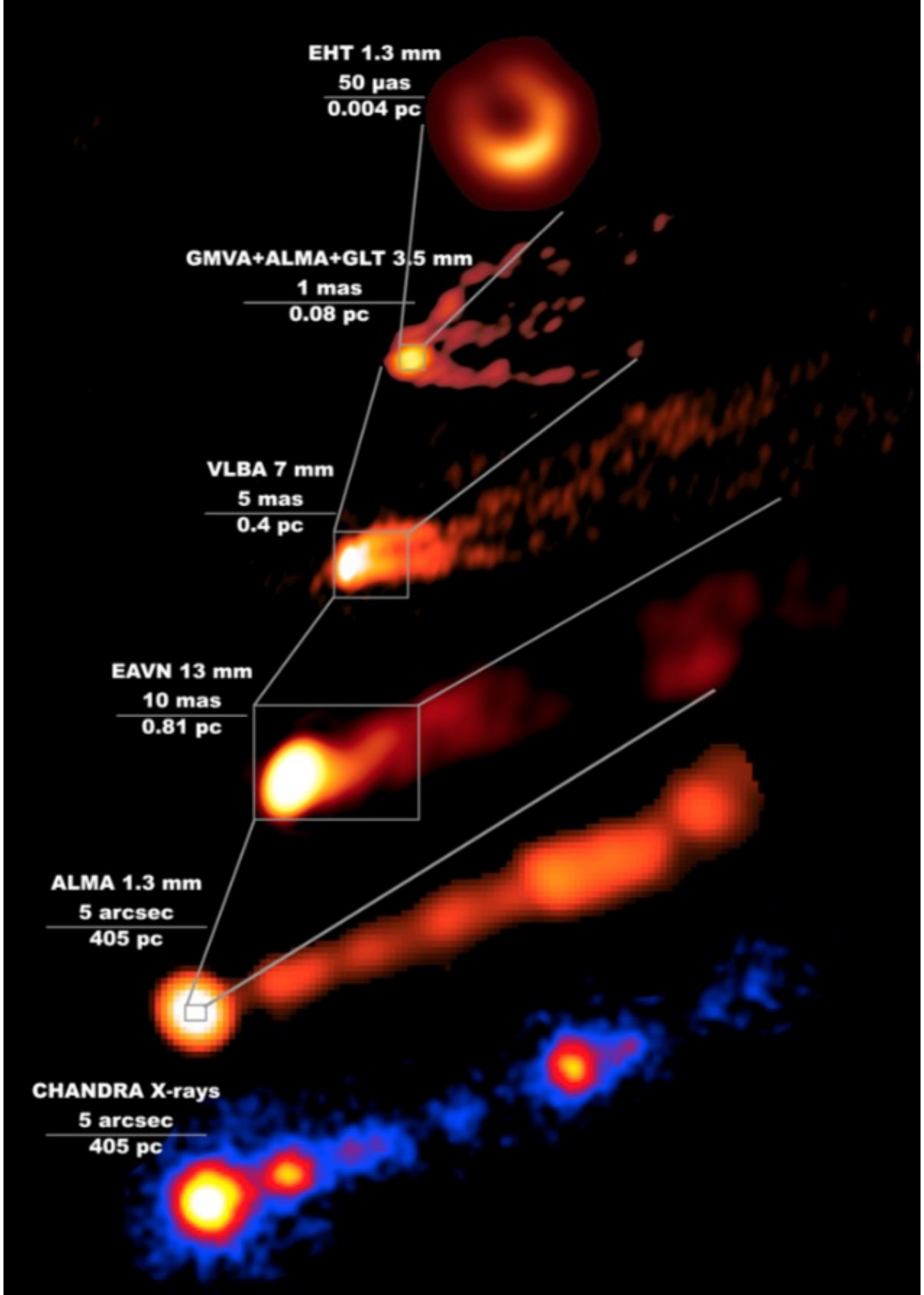
(a) (b) (c) (d)

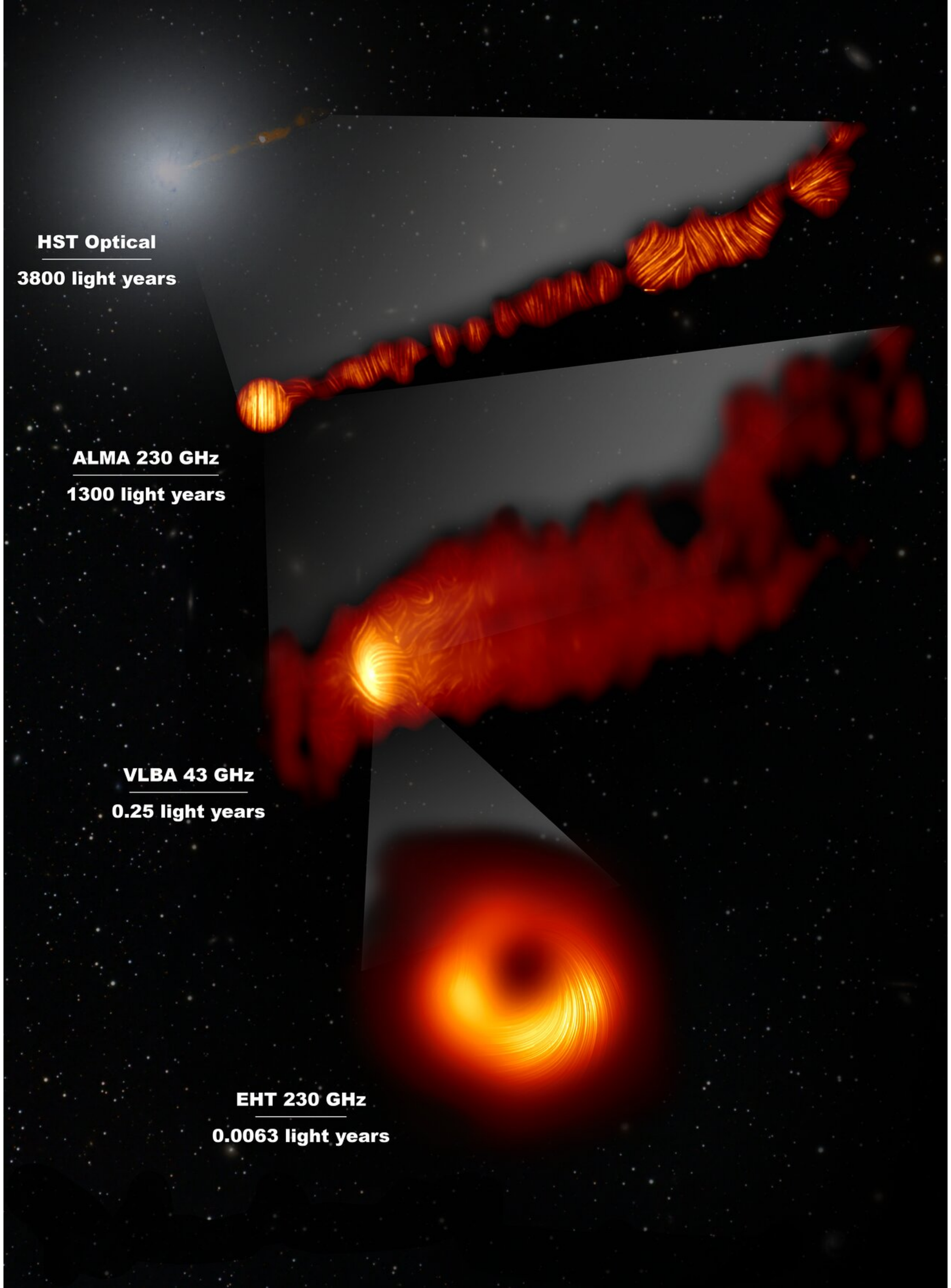
11.4 Two viewpoints on the *Blandford-Znajek process* by which a spinning, magnetized black hole can produce jets. (a) The hole's spin creates a swirl of space which forces magnetic fields threading the hole to spin. The spinning fields' centrifugal forces then accelerate plasma to high speeds (compare with Figure 9.7d). (b) The magnetic fields and the swirl of space together generate a large voltage difference between the hole's poles and equator; in effect, the hole becomes a voltage and power generator. This voltage drives current to flow in a circuit. The circuit carries electrical power from the black hole to the plasma, and that power accelerates the plasma to high speeds.




B
~10⁷cm
Disk
~10¹¹cm
Bondi
radius
~10¹⁵cm

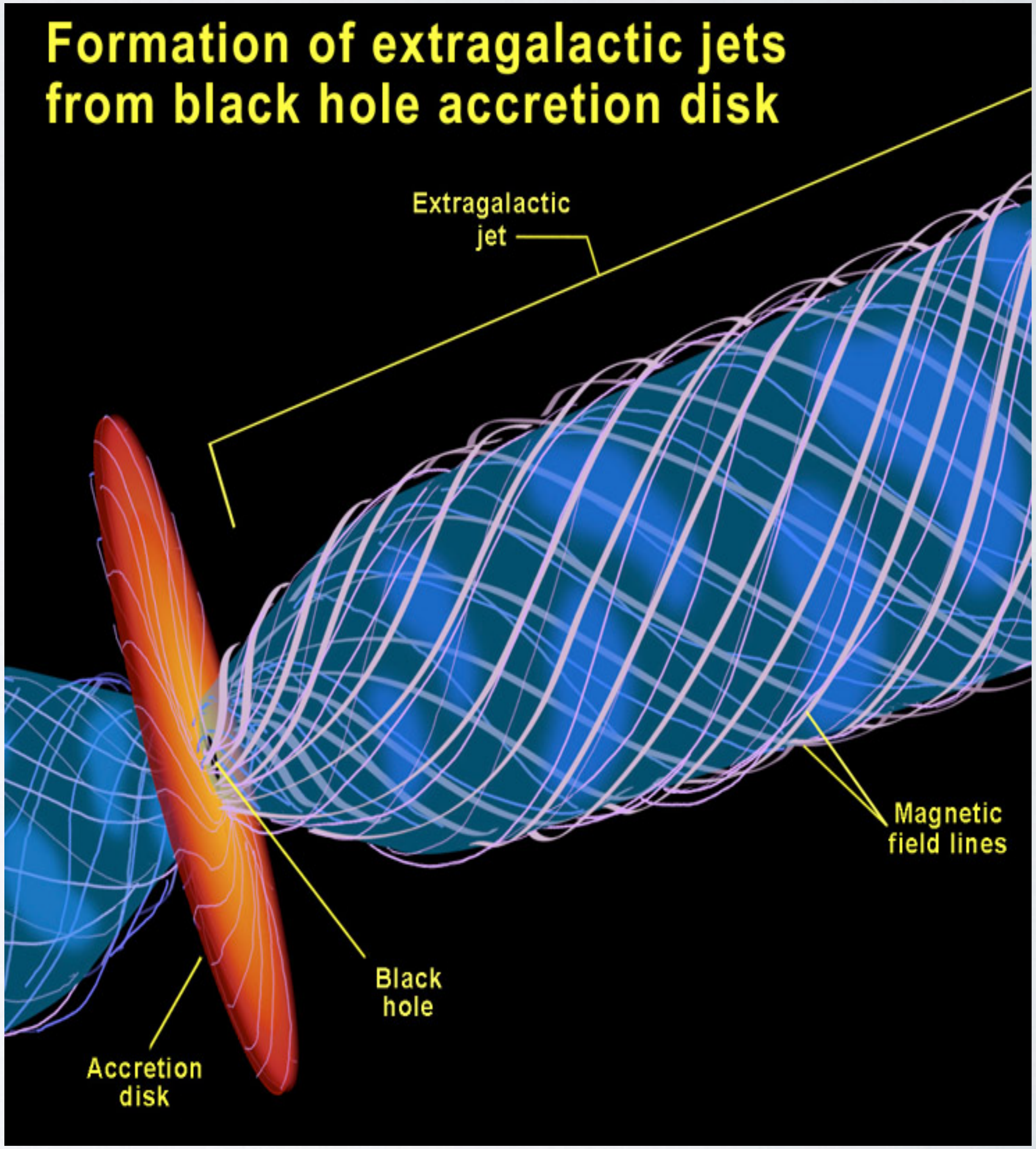



EHT 1.3 mm
50 µas
0.004 pc
GMVA+ALMA+GLT 3.5 mm
1 mas
0.08 pc
VLBA 7 mm
5 mas
0.4 pc
EAVN 13 mm
10 mas
0.81 pc
ALMA 1.3 mm
5 arcsec
405 pc
CHANDRA X-rays
5 arcsec
405 pc

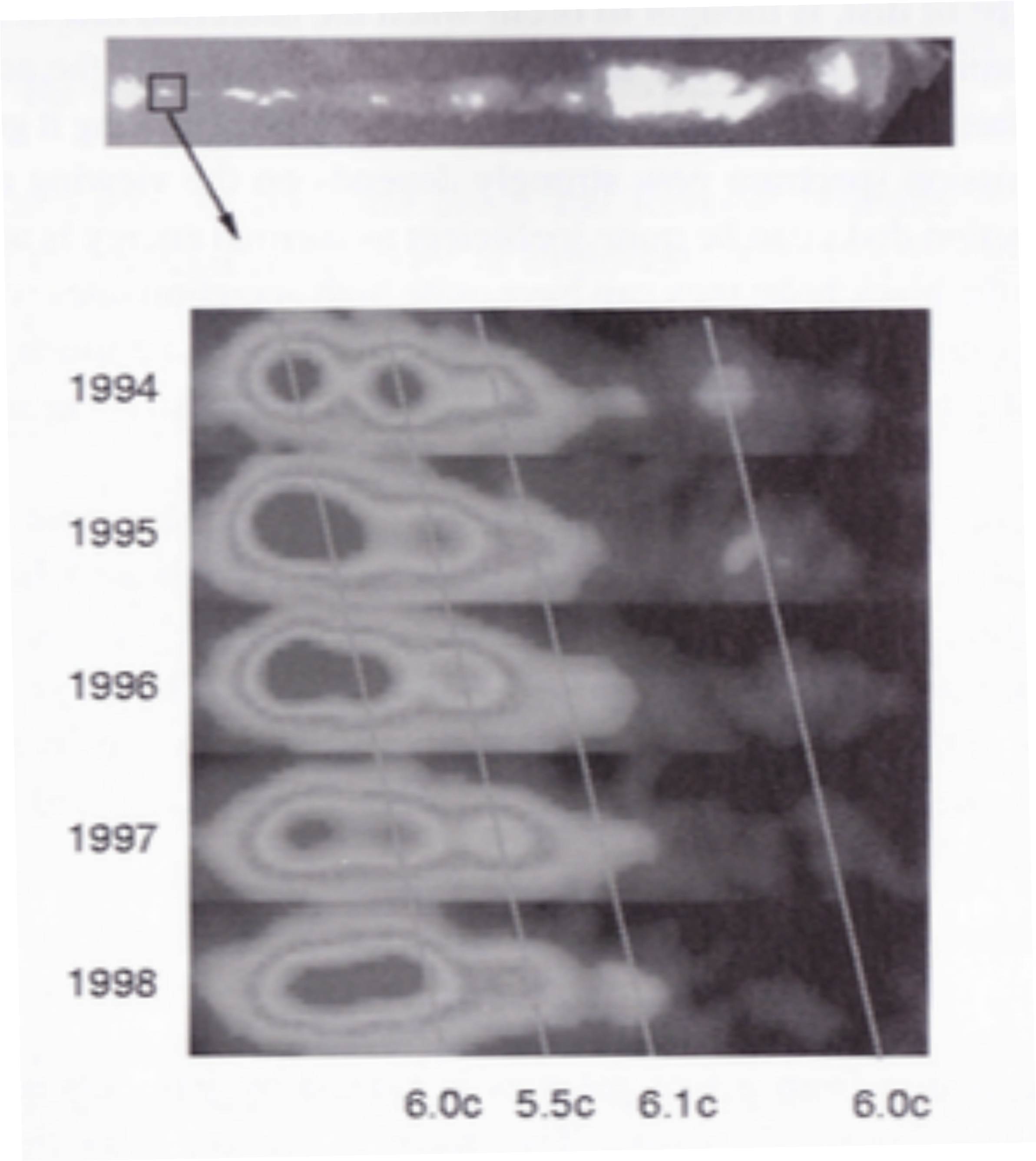

HST Optical
3800 light years
ALMA 230 GHz
1300 light years
VLBA 43 GHz
0.25 light years
EHT 230 GHz
0.0063 light years

Jets

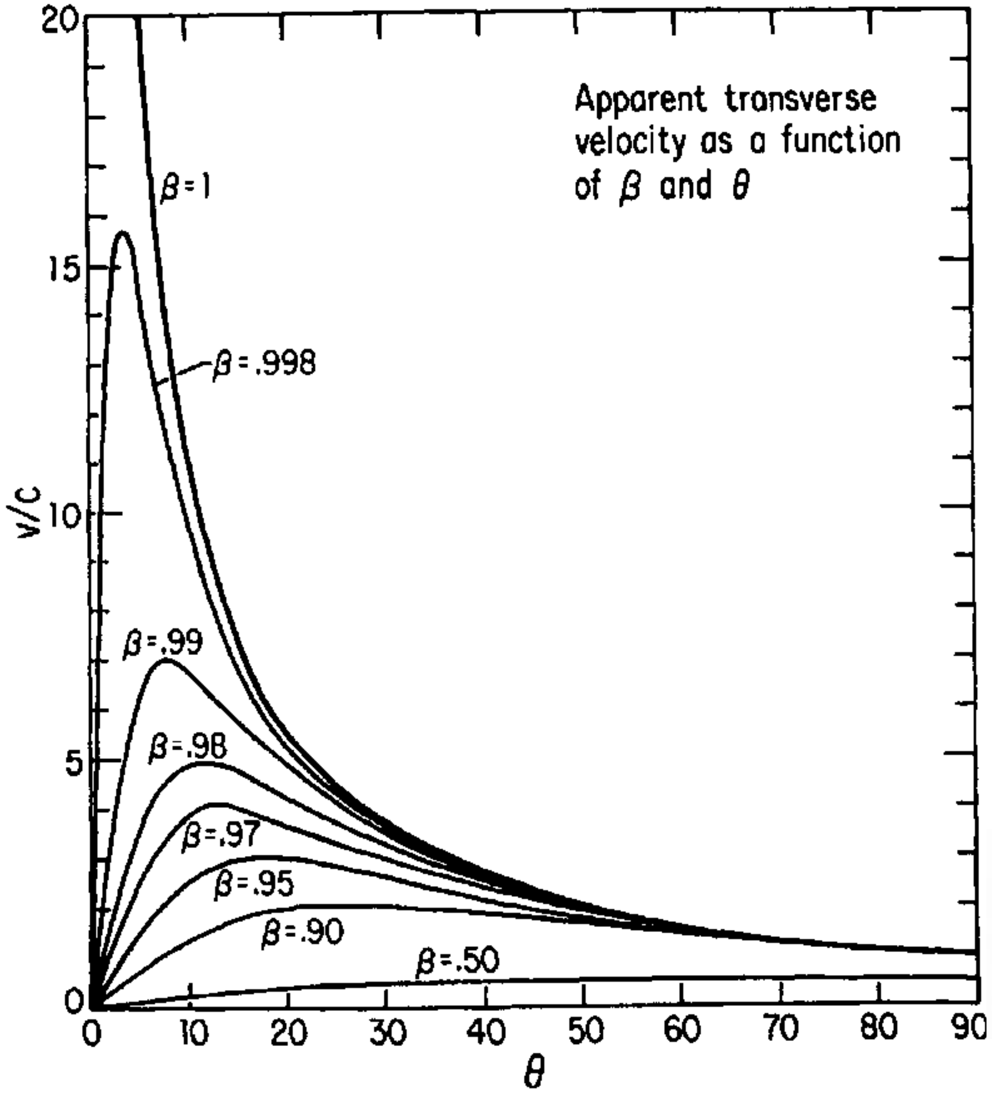
- Not well understood
- Emitted from axis of rotation
- Acceleration through magnetic fields
- Acceleration of charged particles from strong magnetic fields and radiation pressure
- Synchrotron Radiation
  - Produces radiation at all wavelengths especially at Radio wavelengths
- Possible source of Ultra high energy cosmic rays and neutrinos

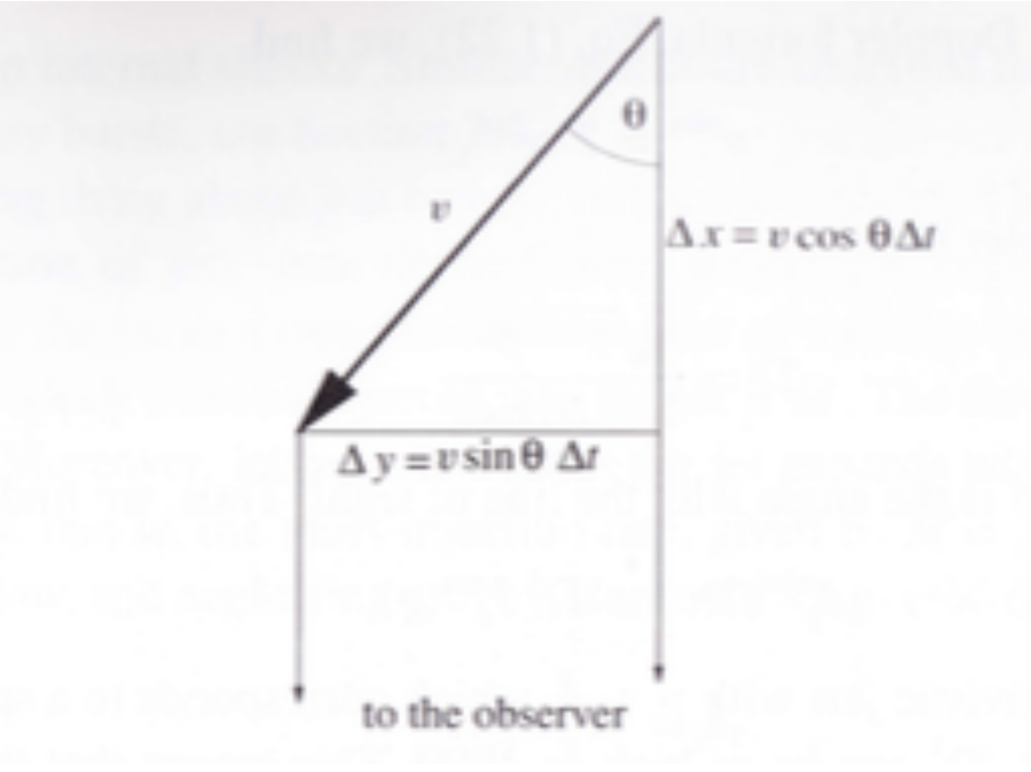


Superluminal motions



Superluminal motions





$$\frac{\Delta y}{\Delta t} = v \sin\theta. \qquad \Delta t_{\mathrm{obs}} = \Delta t - \frac{\Delta x}{c} = \Delta t(1 - \beta\cos\theta),$$

$$v_{\mathrm{app}} = \frac{\Delta y}{\Delta t_{\mathrm{obs}}} = \frac{v \sin\theta}{1 - \beta\cos\theta}$$

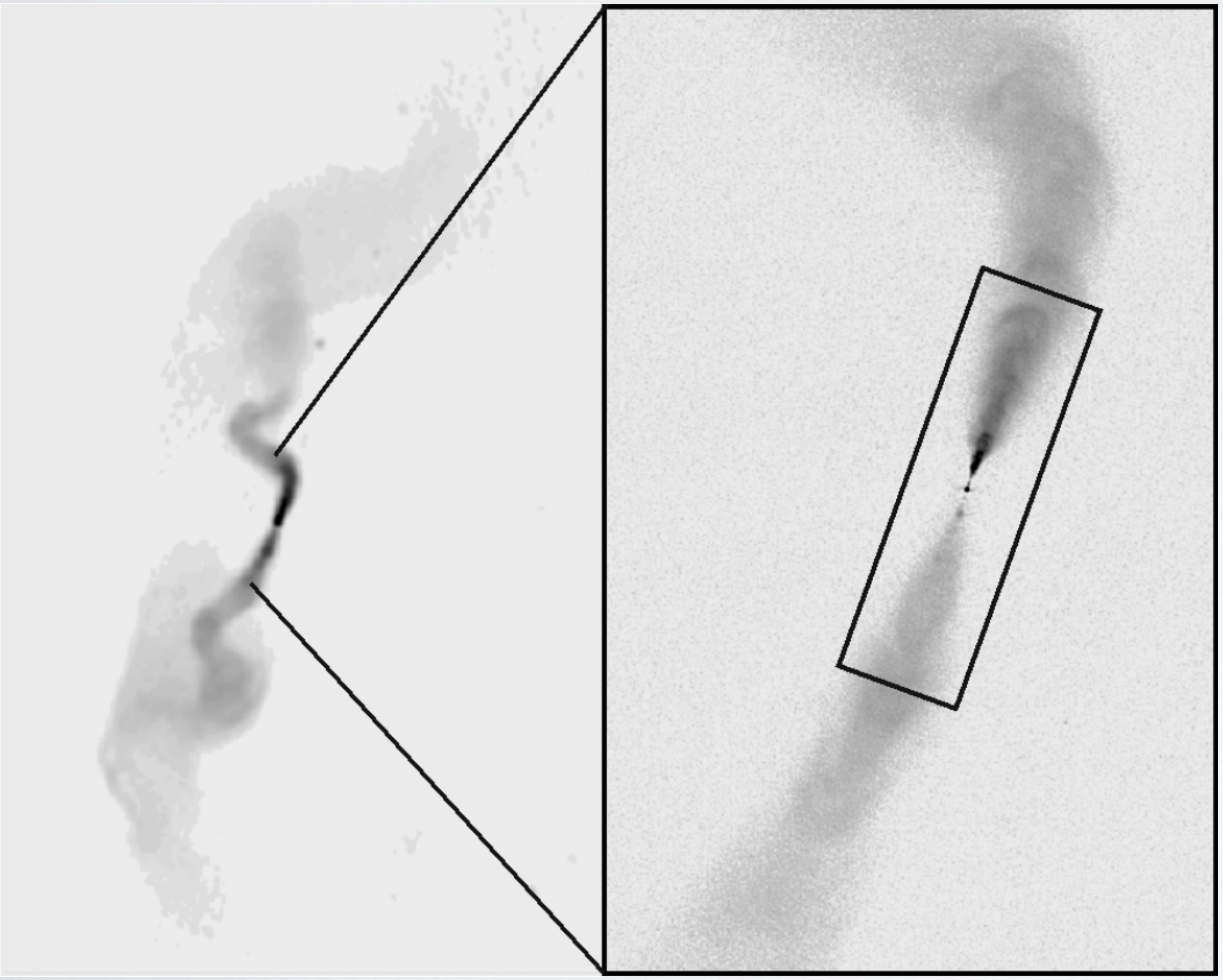
<u>These projection effects explain:</u>

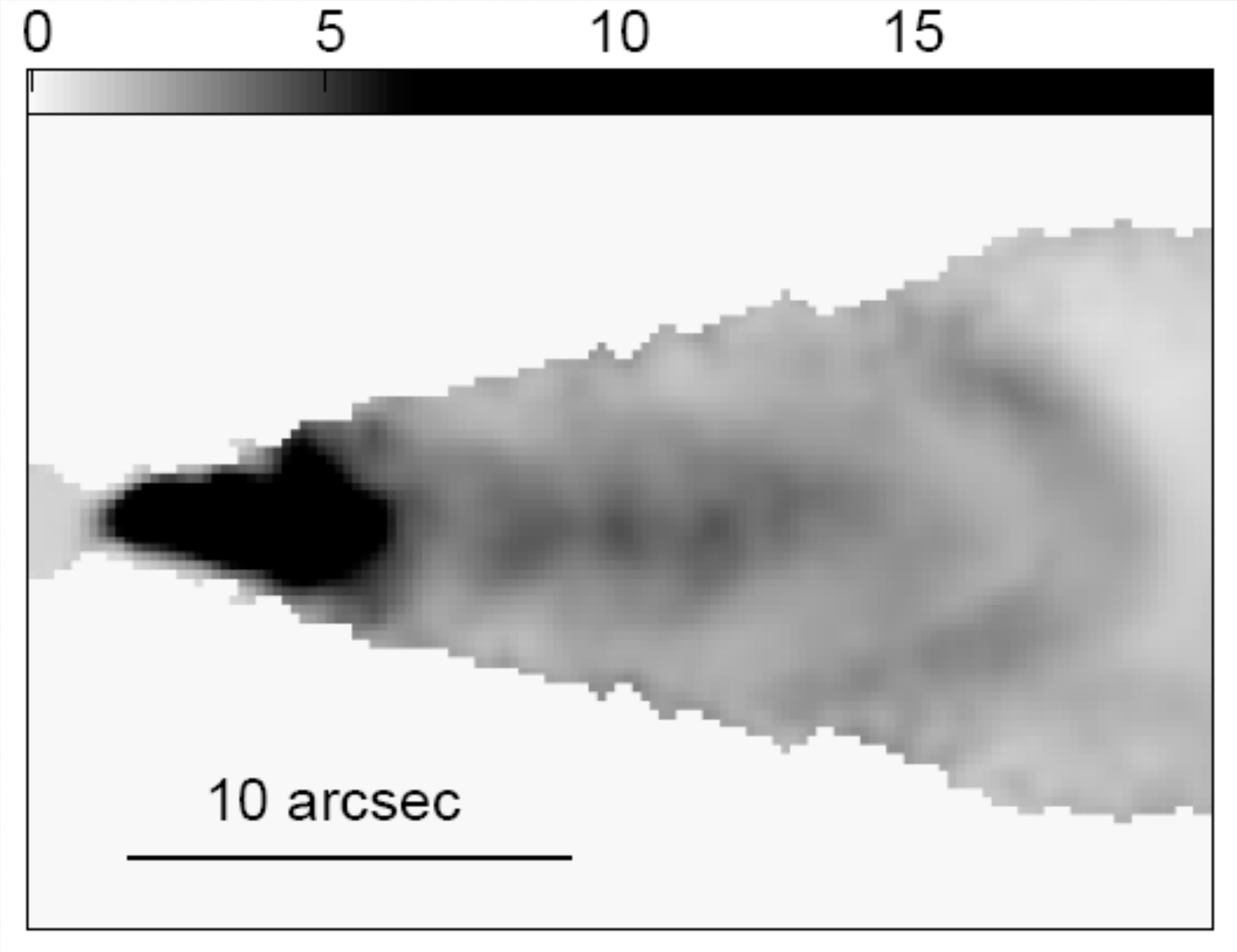
the apparent <u>superluminal motion</u>

§ the <u>asymmetry between the two jets</u>, also the flux of the approaching and receding components are affected by projection (Doppler Boosting)

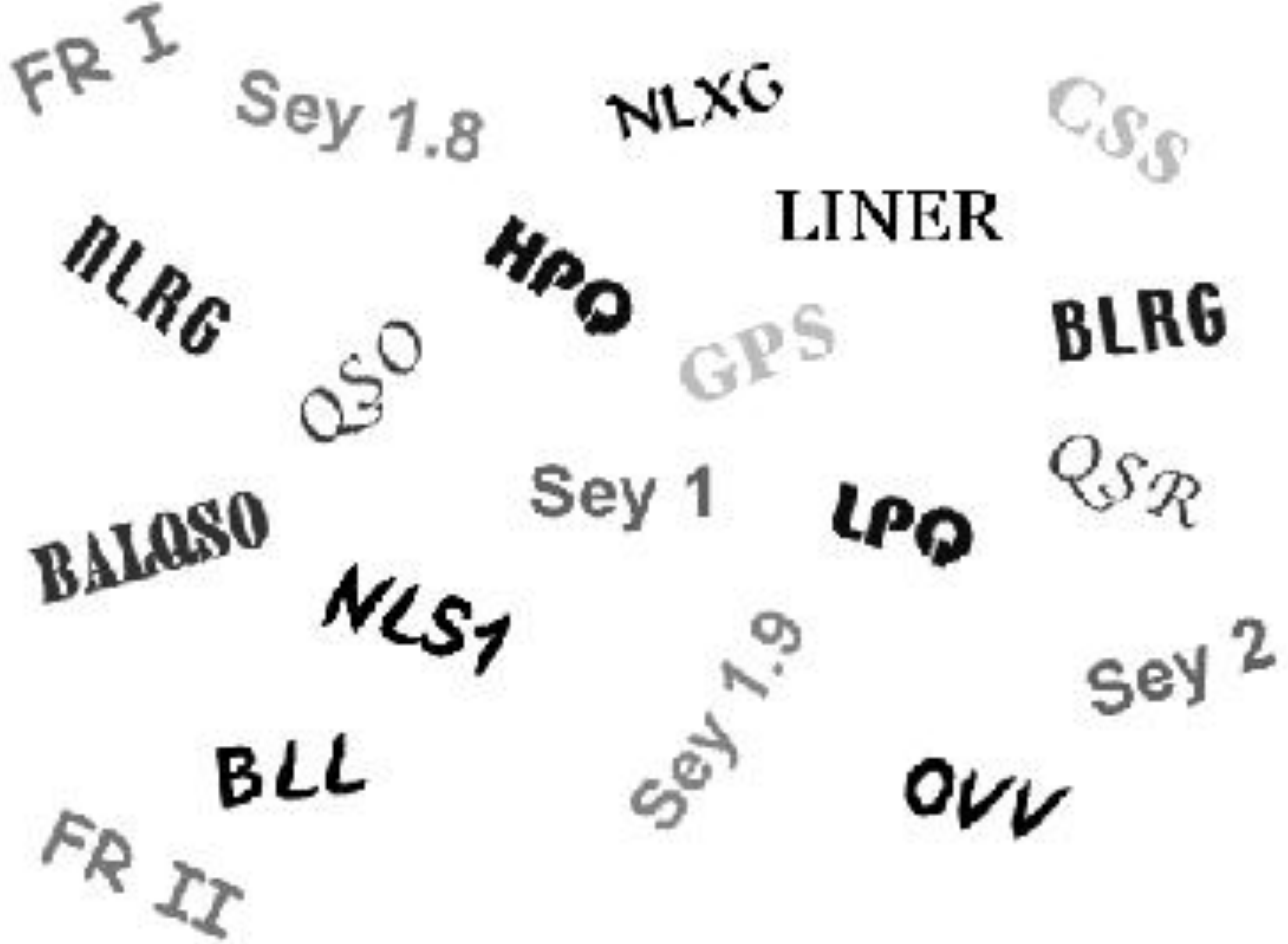
These are among the methods used to find out the orientation of a source

JET TO COUNTER JET RATIOS: BOOSTING & DE-BOOSTING





How to make sense of this ZOO of AGN???



How can we bring all of these types of AGN into a (single) framework?

- **The observed differences might be due to:**
  - Orientation
  - Time evolution
  - Black hole mass
  - Black hole spin
  - Availability of fuel
  - Interaction ambient medium

Unification I

- Radio observations: Radio loud/quiet

  Physics: BH mass + accretion mode(?)
- Spectroscopy: Narrow-line/broad-line/featureless

  Physics: orientation
- Optical Images: dominance of AGN over the galaxy

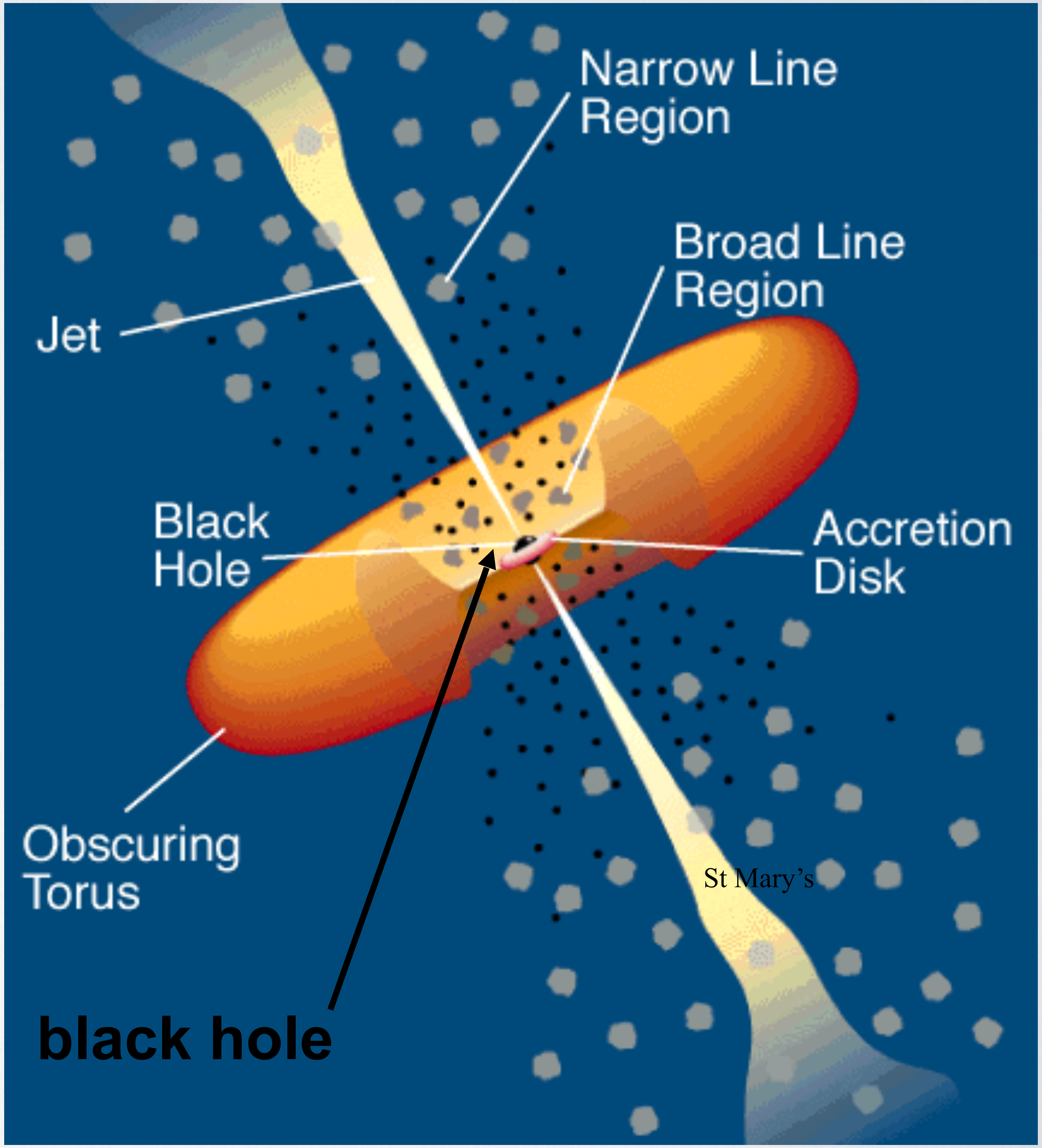
  Physics: degree of central activity: BH mass + Food

The Unified Model of AGNs

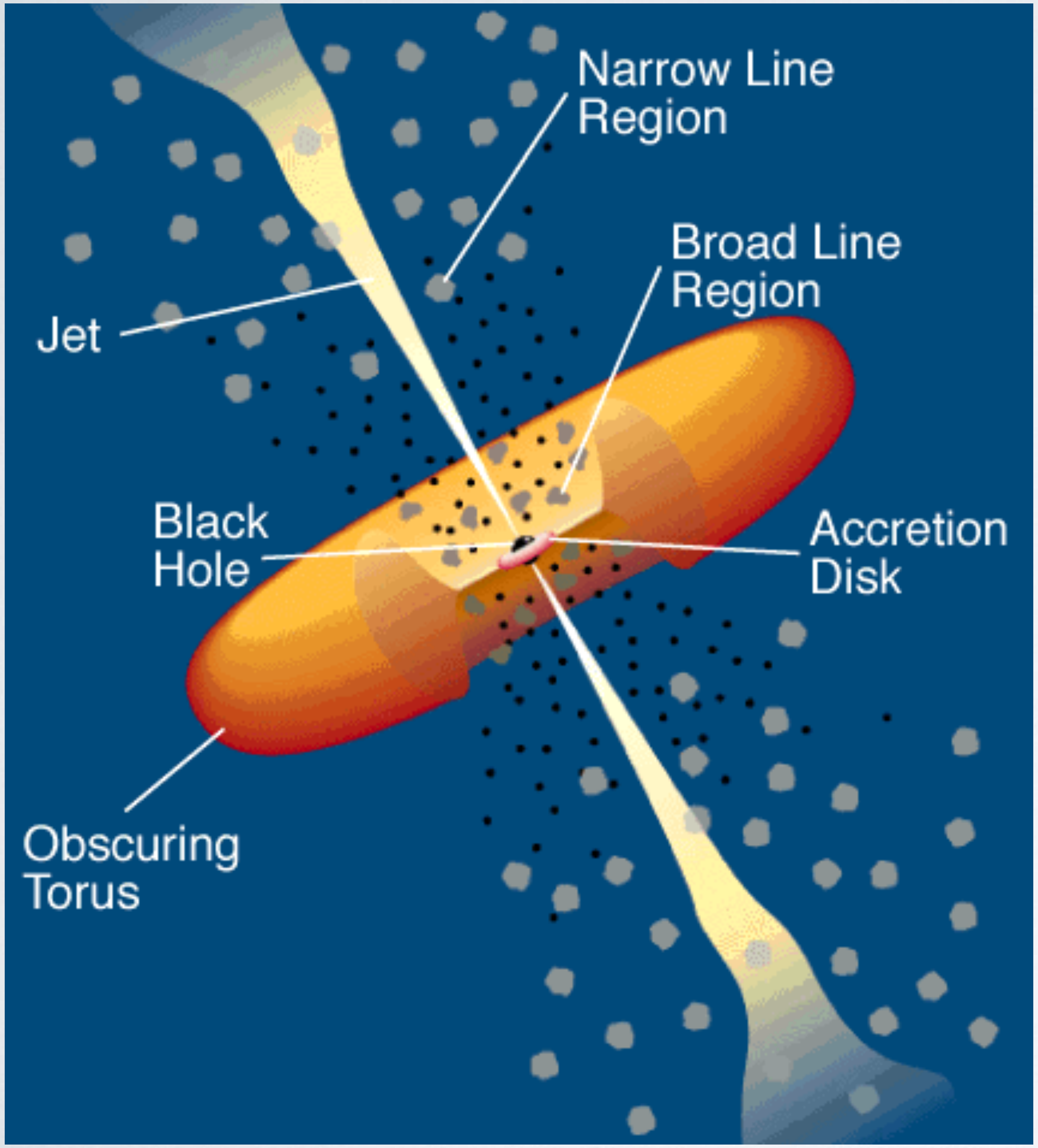
- Radio galaxies, quasars, blazars, Seyferts, etc. are the same type of object with different accretion modes viewed from different angles.

- Centre of a galaxy is a black hole surrounded by an accretion disk, clouds of gas and a dusty torus.

- The energy output comes from accretion of material onto the black hole.



The standard model of AGN



Components:

- Accretion disk:

  r ~ 10^{-3} pc, n ~ 10^{15} cm^{-3}, v ~ 0.3c
- Broad Line Region (BLR):

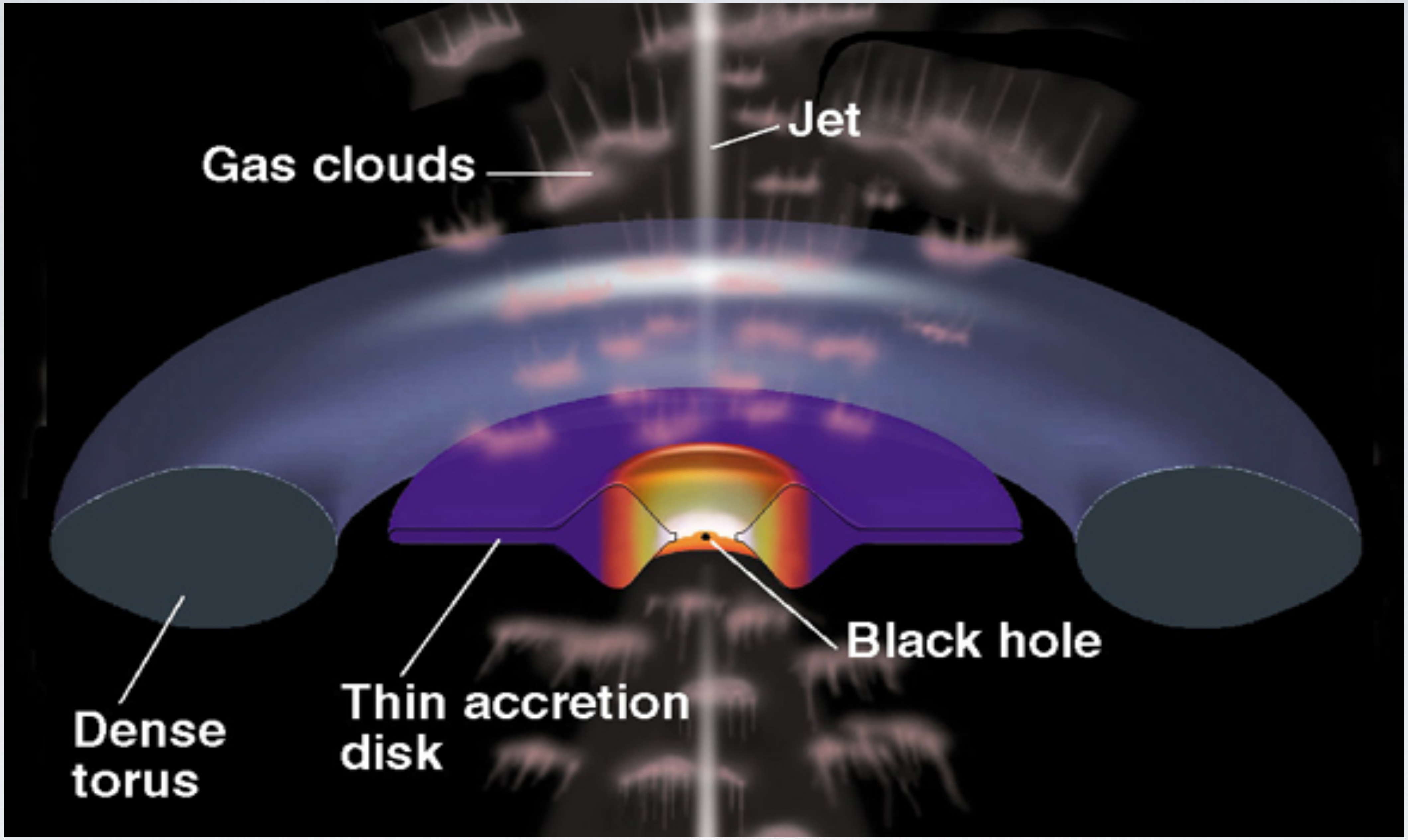
  r ~ 0.01 – 0.1 pc, n ~ 10^{10} cm^{-3},

  v ~ few x 10^3 km s^{-1}
- Torus:

  r ~ 1 – 100 pc, n ~ 10^3 – 10^6 cm^{-3}
- Narrow Line Region (NLR):

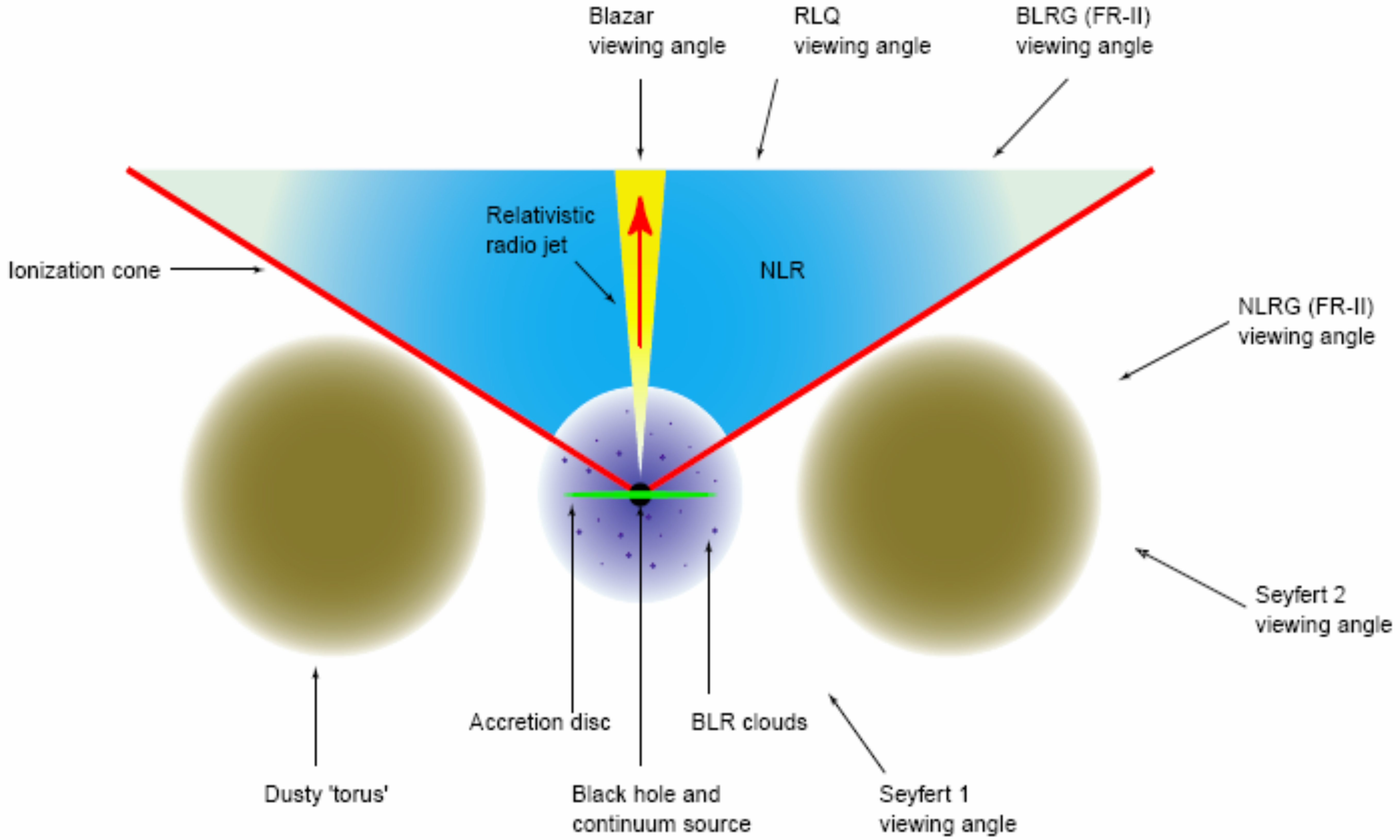
  r ~ 100–1000 pc, n ~ 10^3 – 10^6 cm^{-3},

  v ~ few x 100 km s^{-1}



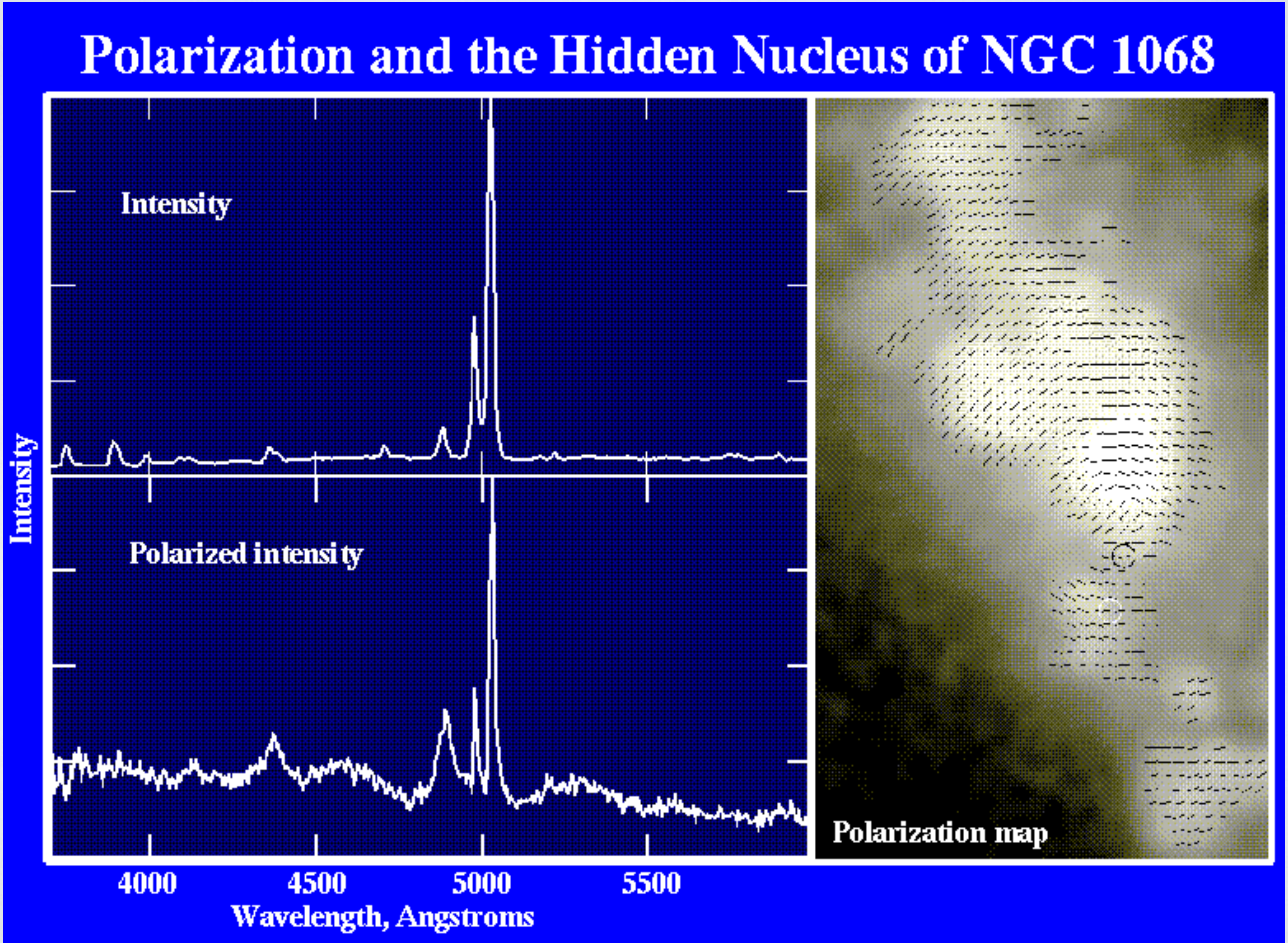
Model for the central region of an active galaxy. A super-massive black hole in the center of the galaxy is surrounded by an accretion disk of infalling material. If conditions are right, the galaxy may also possess a magnetically-confined jet which could be the source of radio emission.

Effects of the orientation to AGN

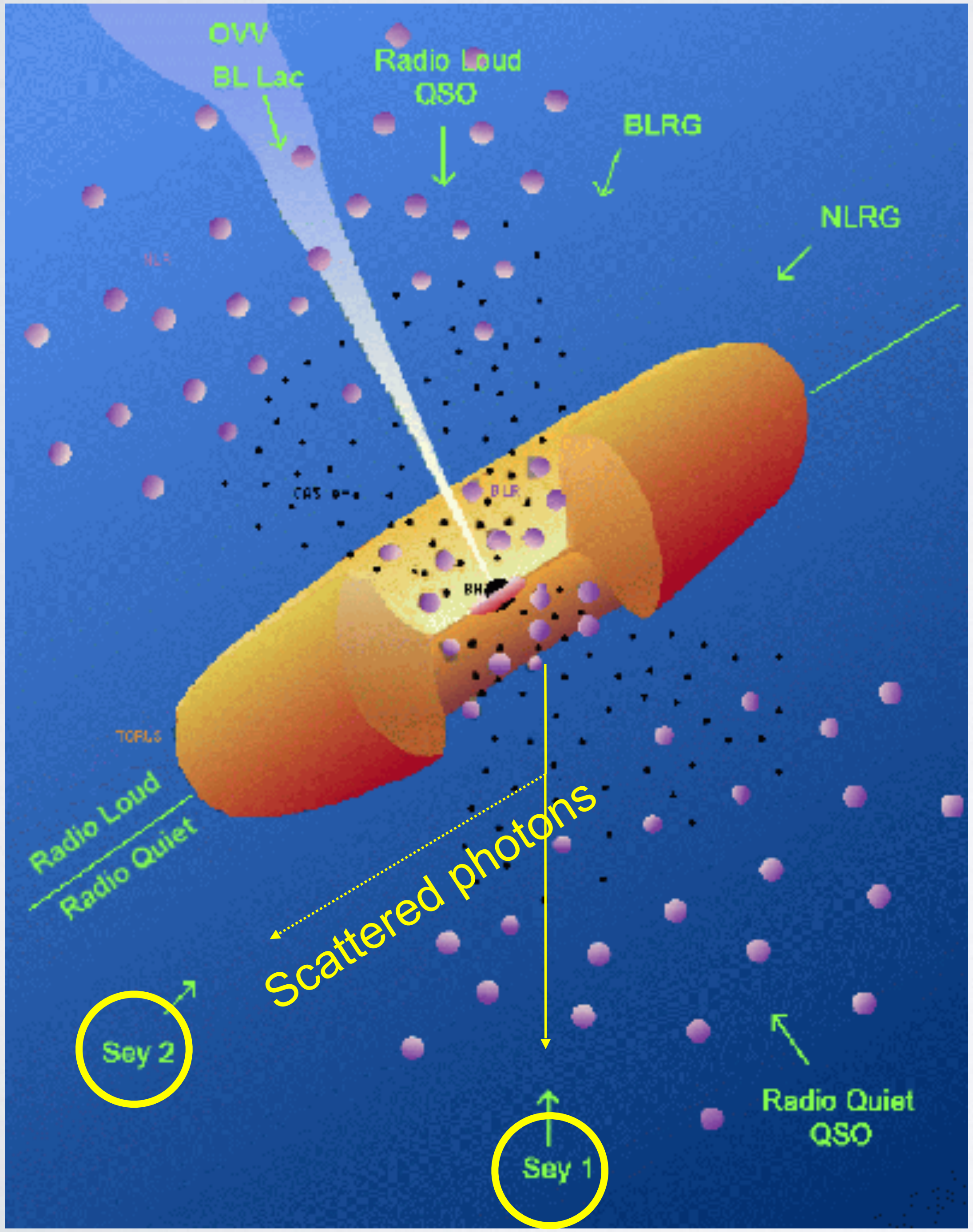


Support for unification: hidden emission lines

Some Sy2s show broad lines in polarized light



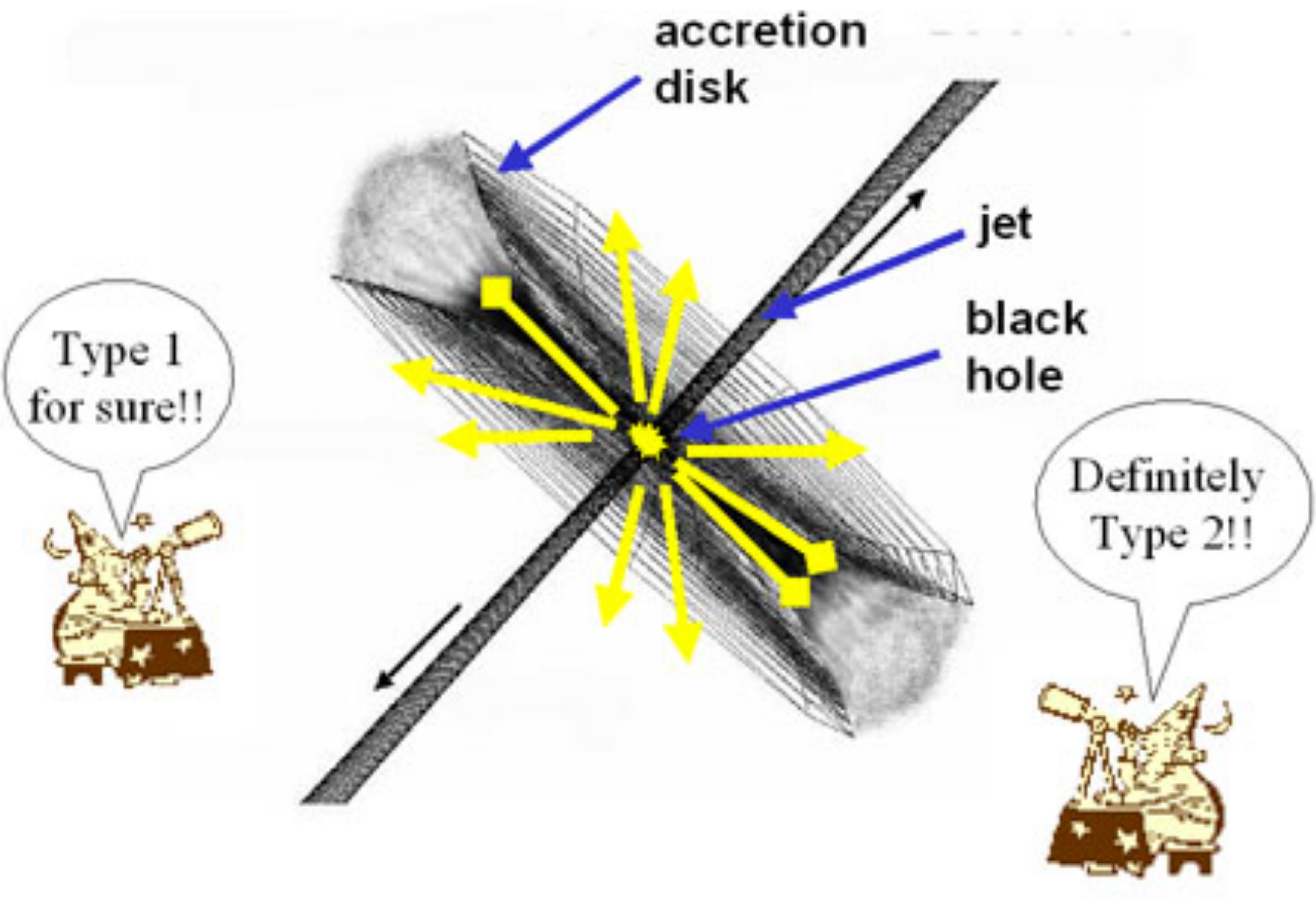
Support for unification: hidden emission lines



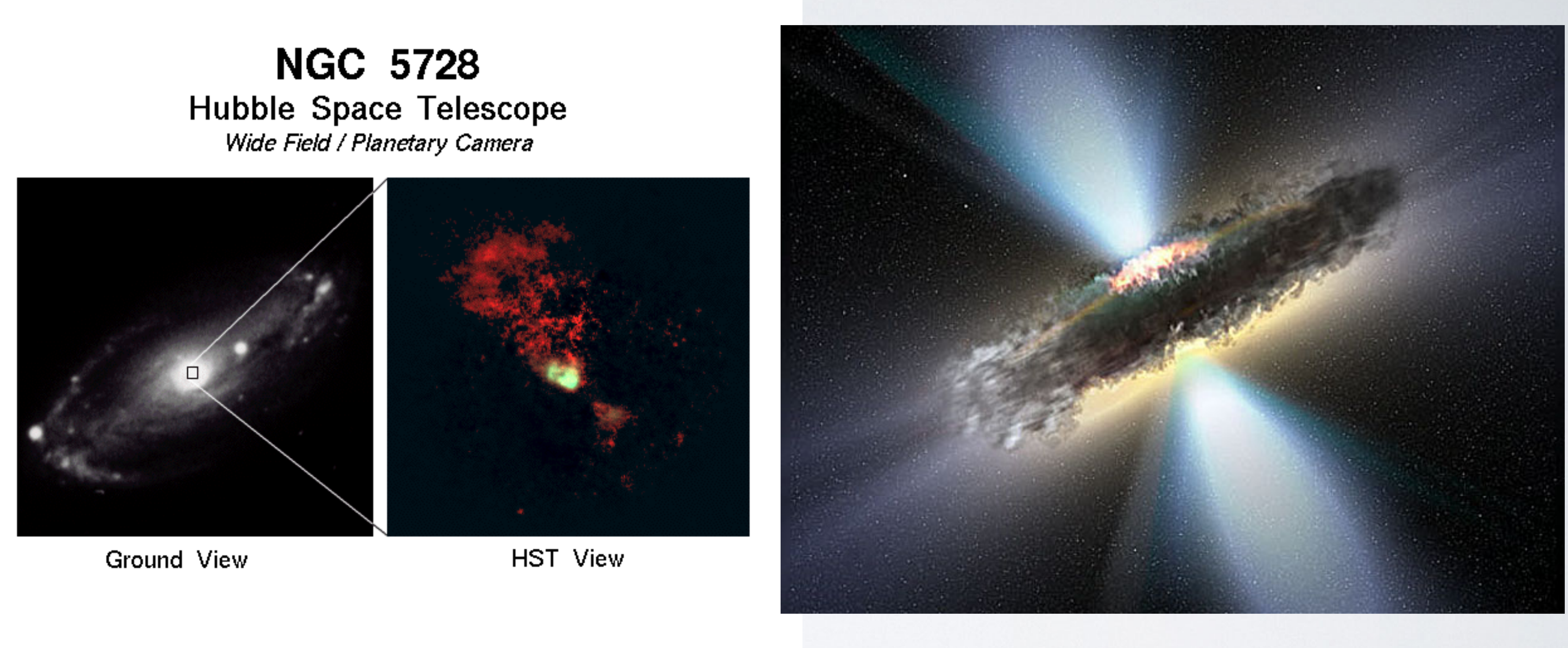
Hot electrons scatter photons from the BLR near the nucleus to the observer. Dust torus shield direct line-of-sight to the nucleus

Hence, Sy2 look a bit like Sy1 in polarized light

Support for unification: hidden emission lines



Support for unification: ionization cones

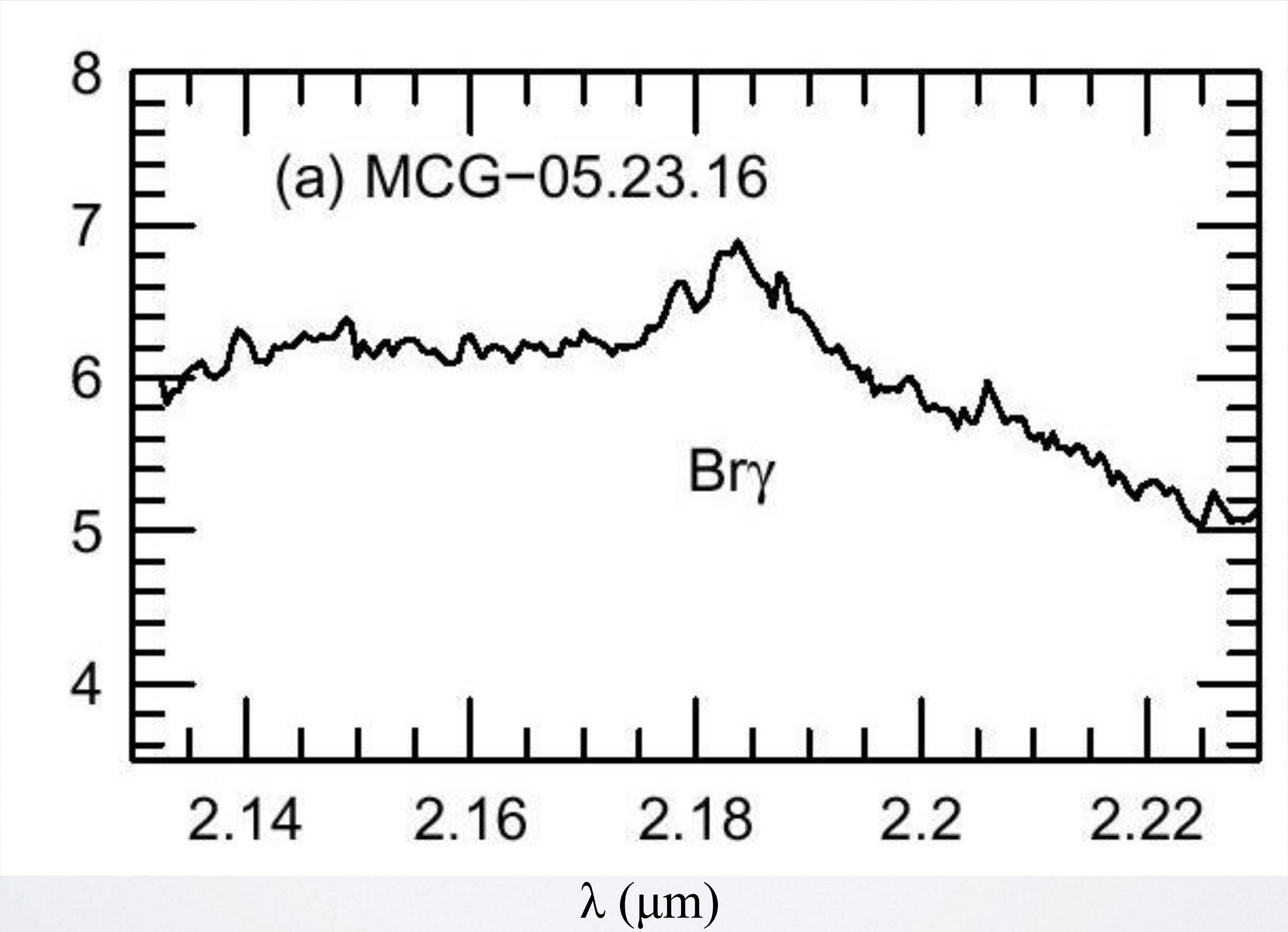


The ultraviolet emission comes from the accretion disk, lighting up a cone of glowing gas in the galaxy to the left. Only the cone of ultraviolet light can escape from the cavity in the accretion disk where the black hole lies; in other directions, the light is absorbed by the disk. (From STScI, modified by G. Rieke)

Support for unification: broad IR lines

25% of Sy2s show some broad component in the IR

There are searches for broad-recombination lines in the near-IR spectrum of Sy 2s, where the extinction affects the emitted spectrum less.



(Veilleux, Goodrich & Hill 1997)

Support for unification: IR and N_H excess

The column of neutral H that absorbs the soft X-rays emitted by the nucleus is associated with the dust in the molecular torus, and thus provides a rough estimate of the dust content and the attenuation this provides.

Sy2s have the largest absorption columns:

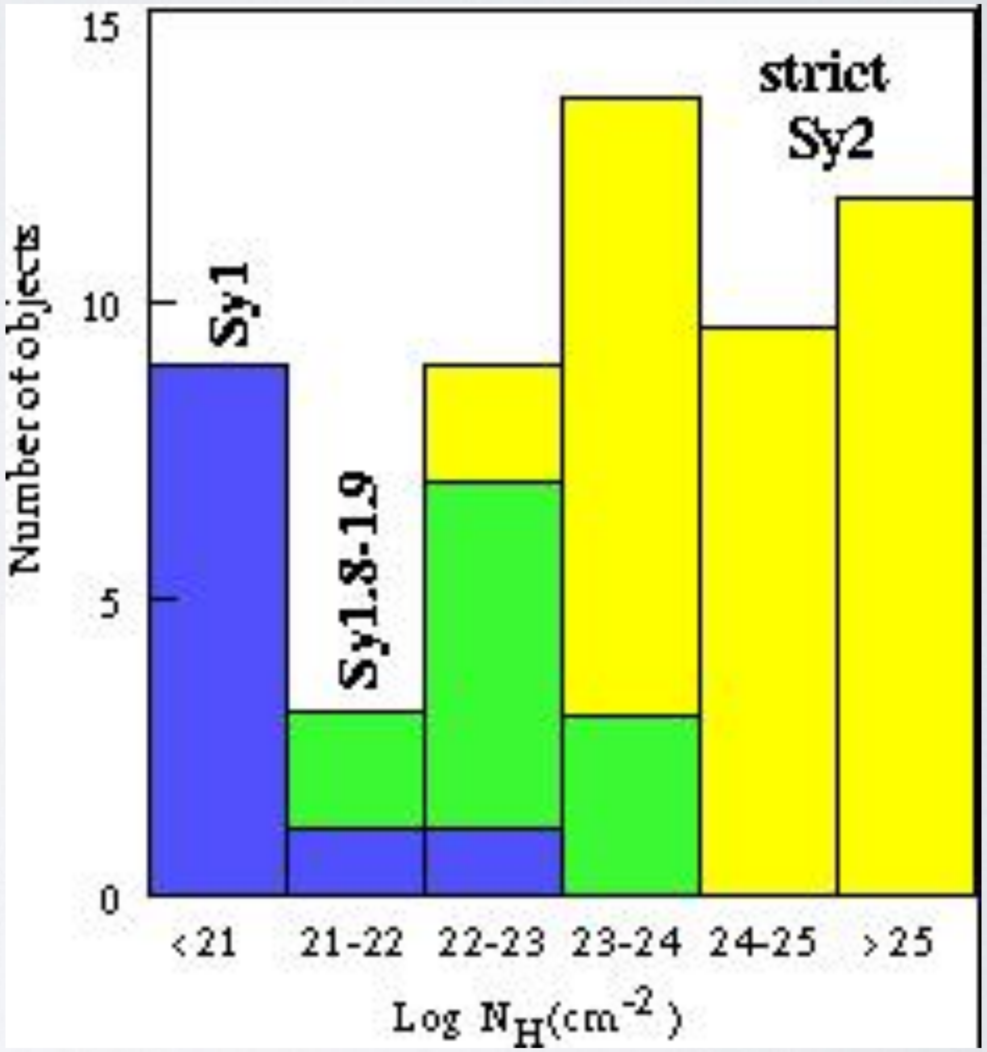
The medium is Compton thick, so that X-rays are suppressed below 10 keV

Sy 2s also have colder IR colours than Sy1s:

Explained if the torus is partially thick at mid-IR wavelengths. (Pérez-García et al. 1998):

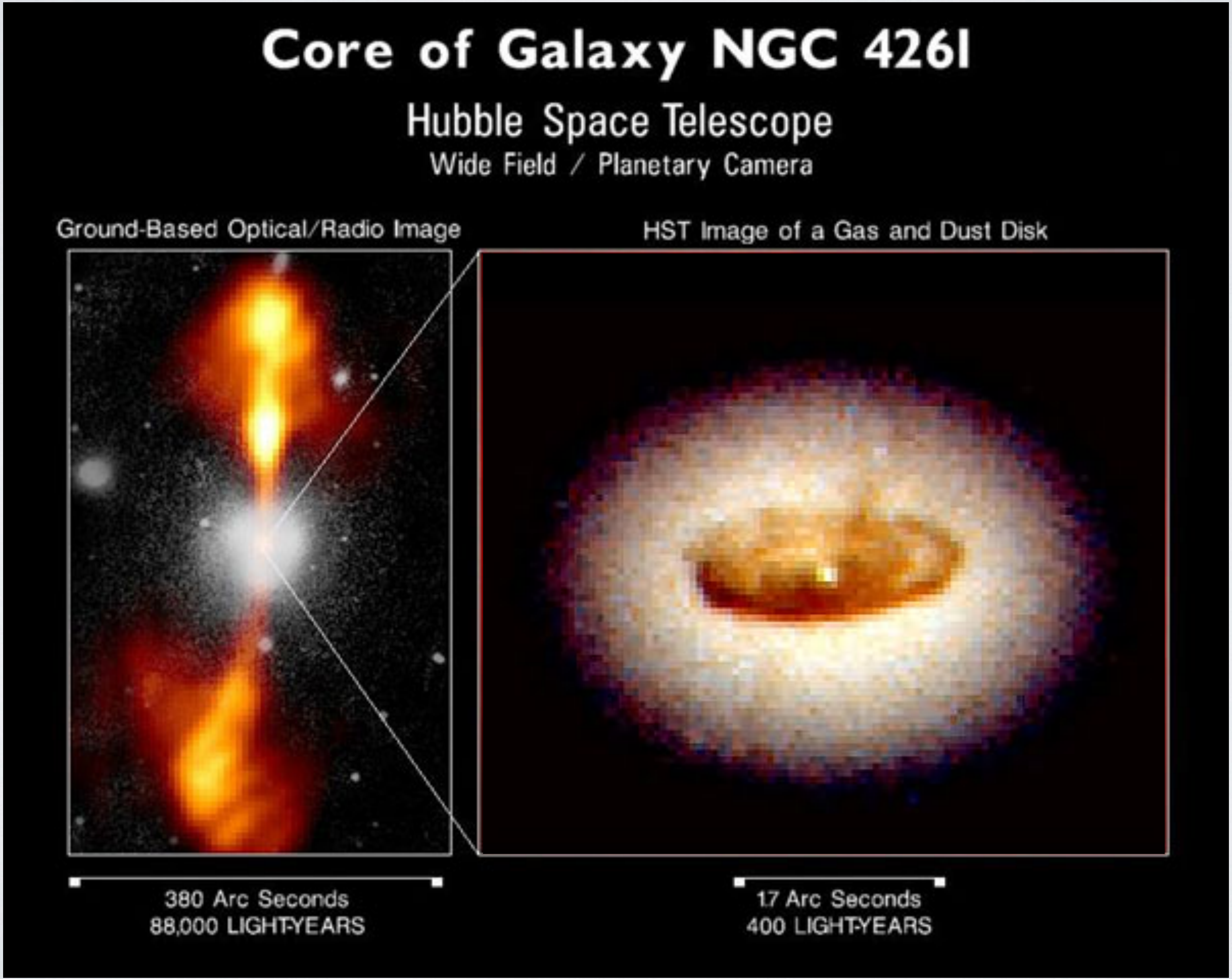
$T_{Sy2}=112 - 136$ K

$T_{Sy1} \approx 150$ K



(Risaliti et al. 1999)

Support for unification: direct imaging of torus?



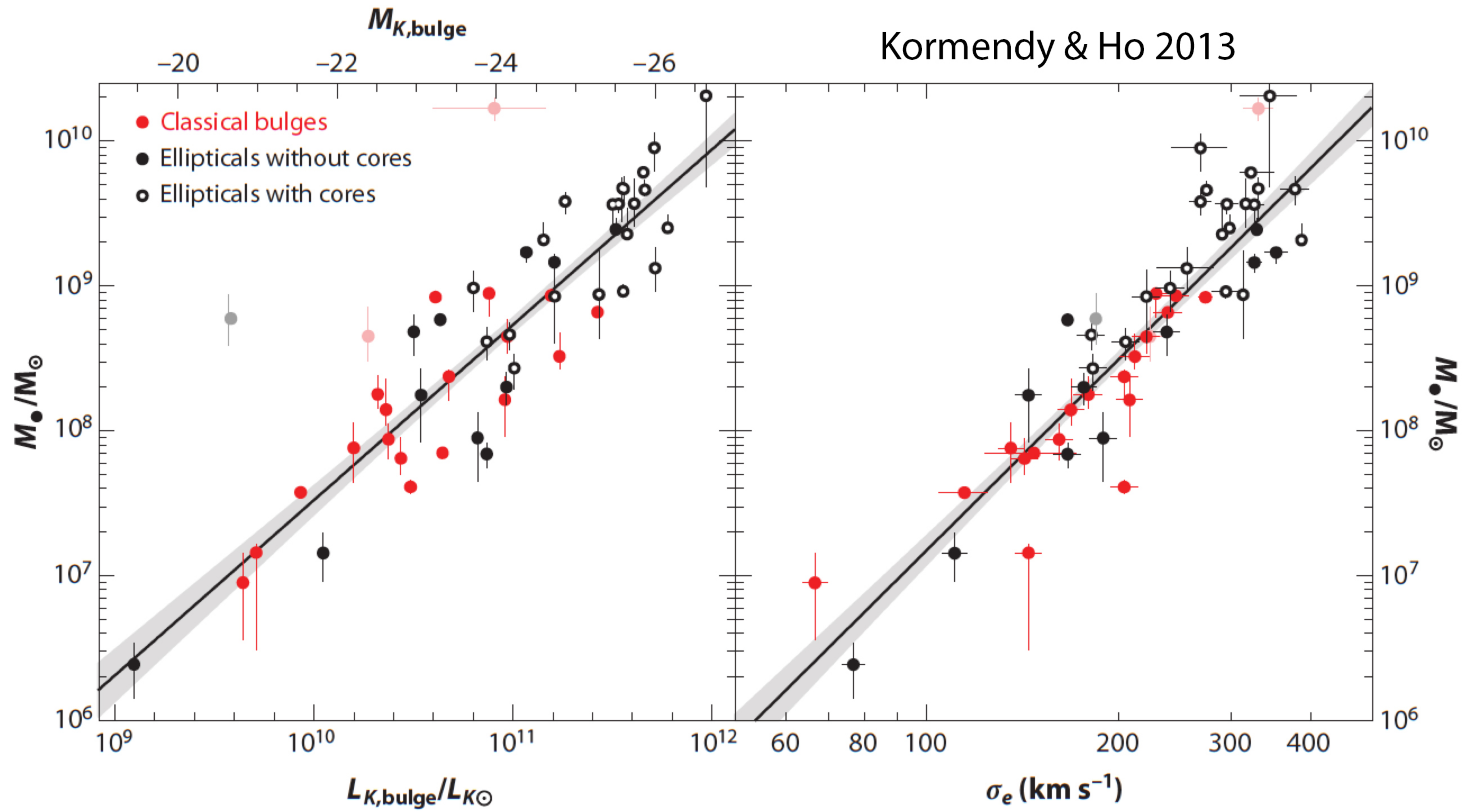
General Summary

- AGN come in many forms and shapes. However, some of their properties cross AGN-type "boundaries"

- This has led to a "Standard Model" of AGN
  - In the centre of the AGN host is a black hole surrounded by an accretion disk, clouds of gas and a dusty torus, from which (sometimes) a jet emanates.

- AGN types are the results of mostly their orientation but also different physical circumstances (why a jet?)

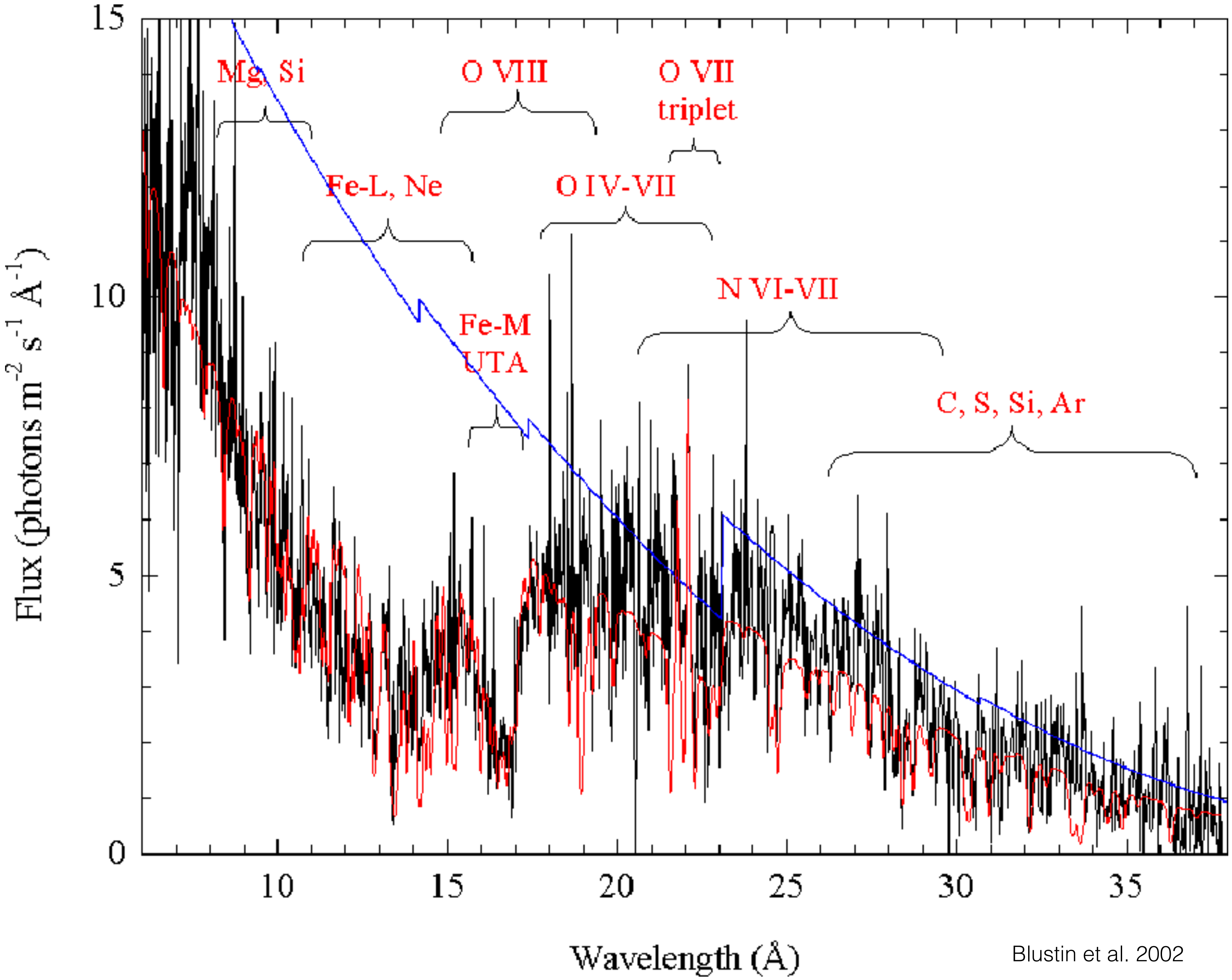
Galactic bulges and black holes grow up together



$M_{\mathrm{BH}}=0.78\mathrm{x}10^8 M_{\mathrm{Sun}}(L_{\mathrm{B,bulge}}/10^{10}L_{\mathrm{B,Sun}})^{1.08}$ $M_{\mathrm{BH}}=1.66\mathrm{x}10^8 M_{\mathrm{Sun}}(\sigma/200\mathrm{kms}^{-1})^{4.86}$

AGN Warm Absorbers

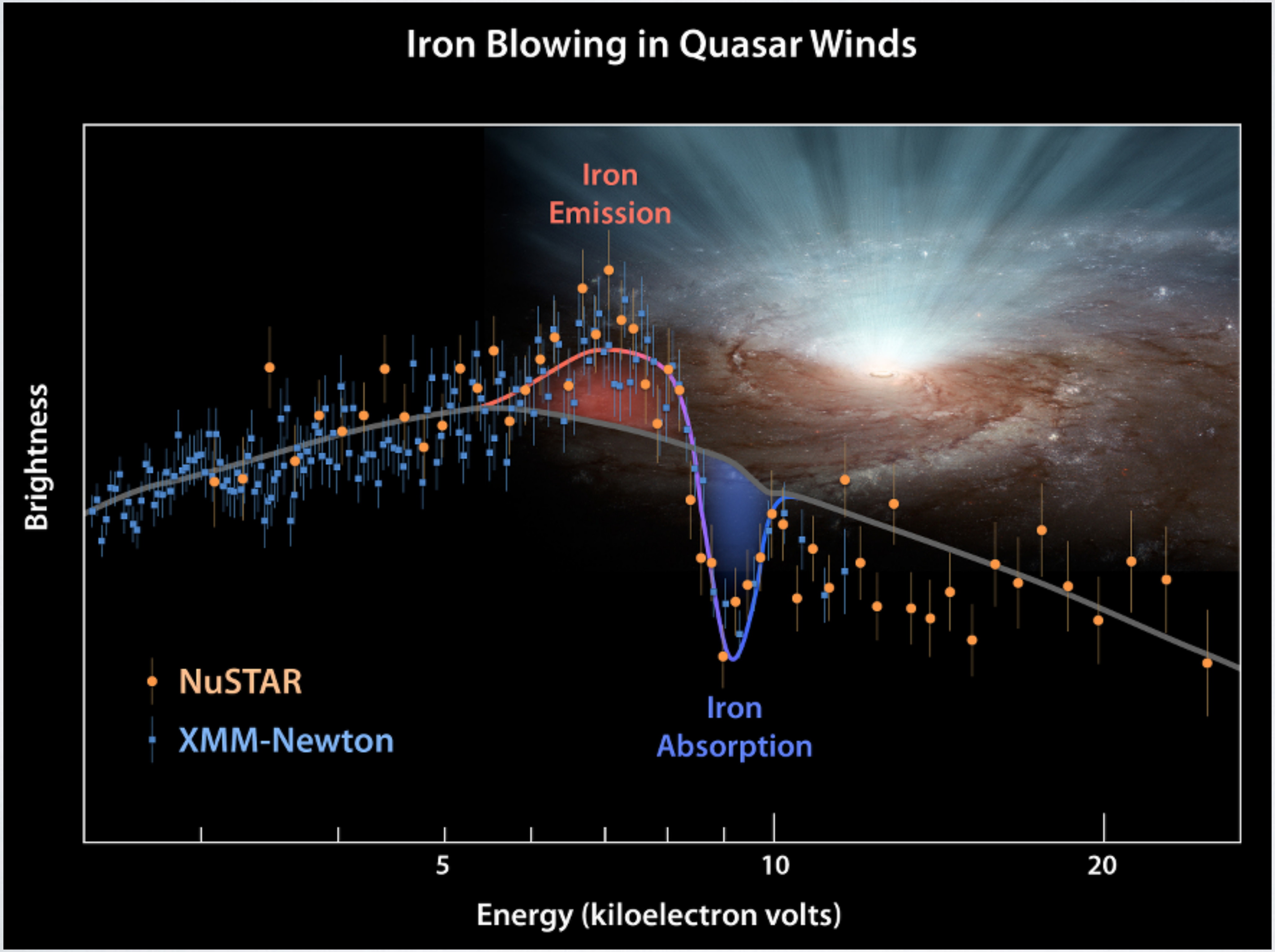
NGC 3783



Blustin et al. 2002

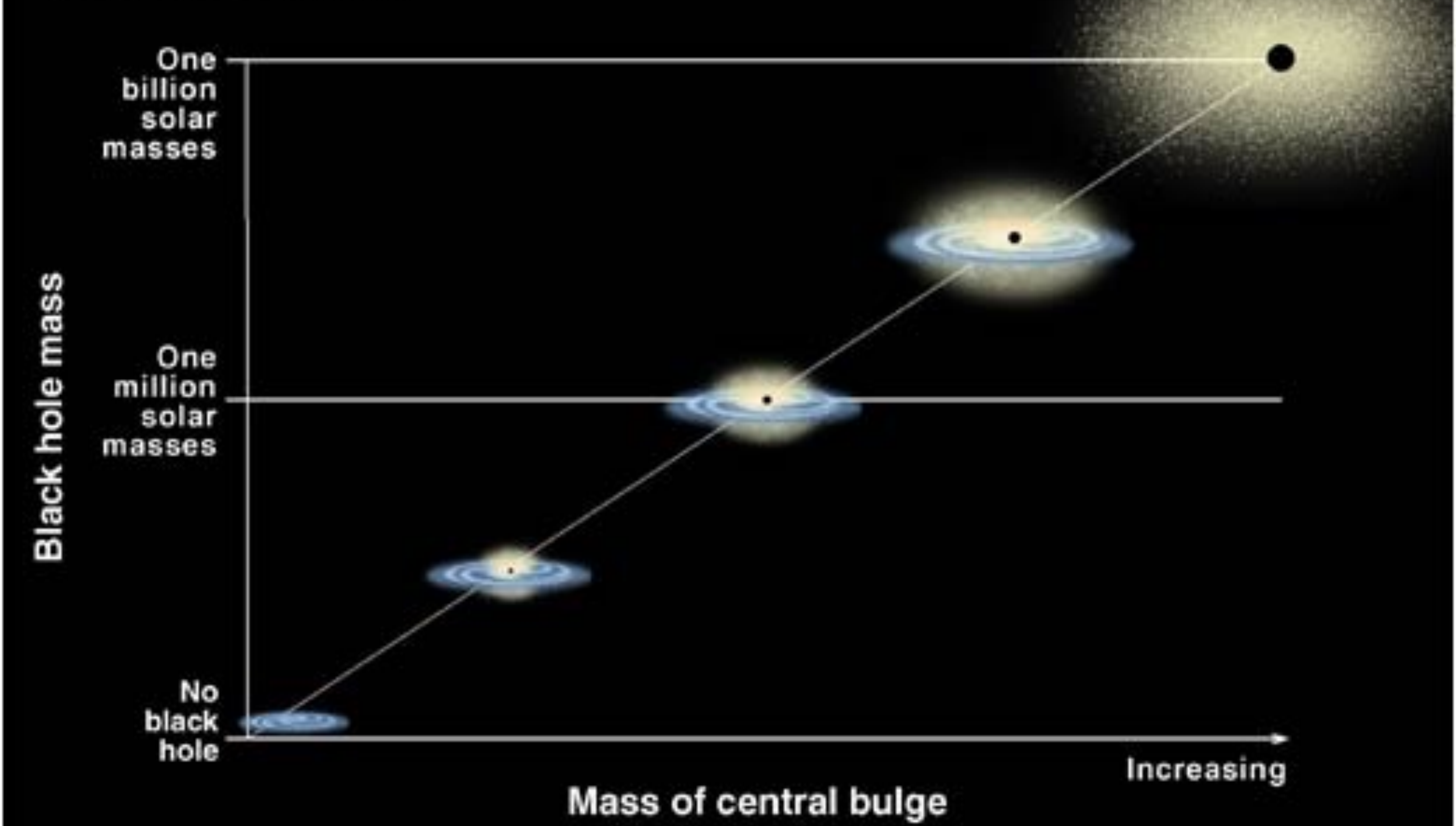
AGN ULTRA-FAST OUTFLOWS

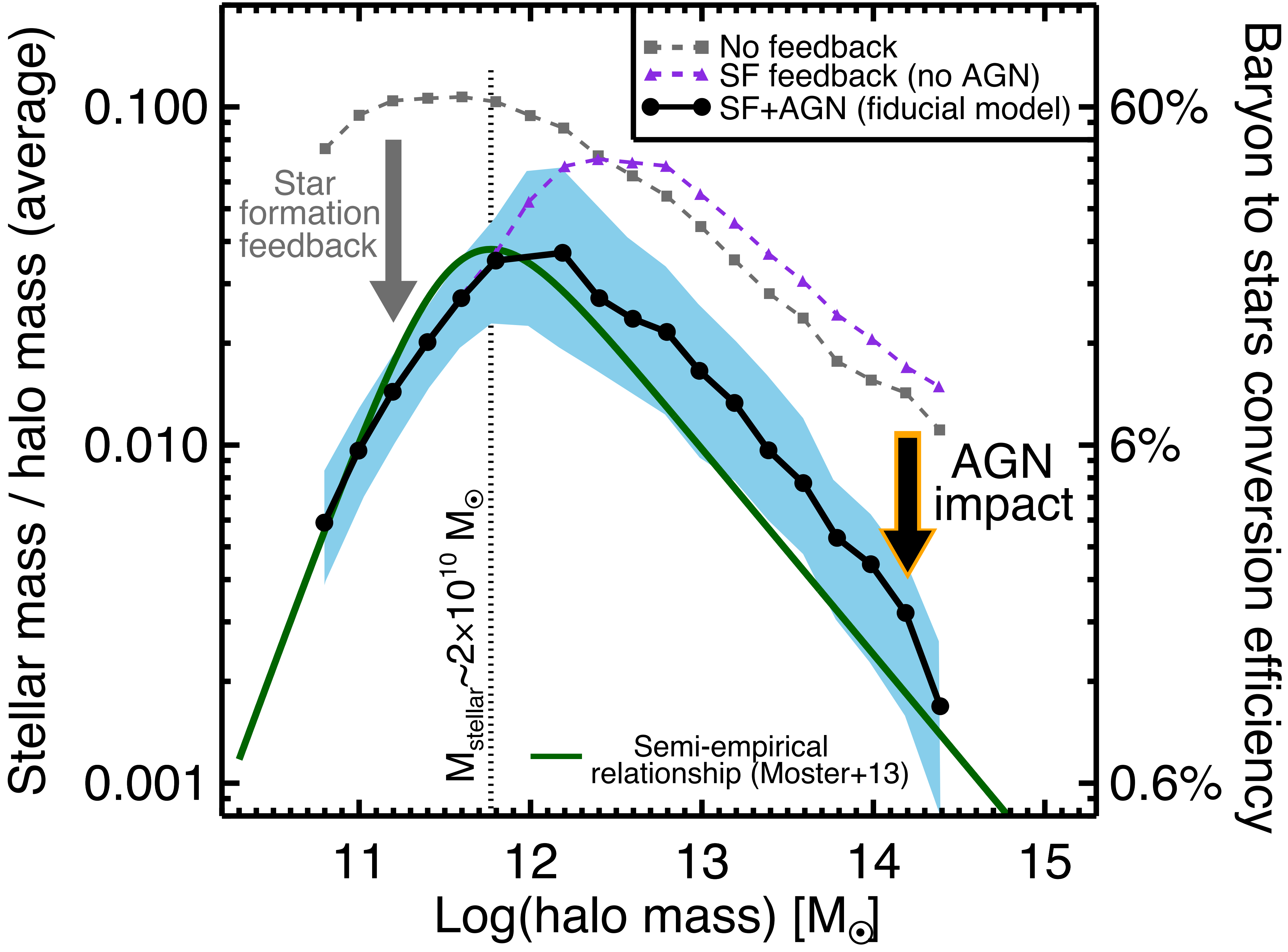
PDS 456



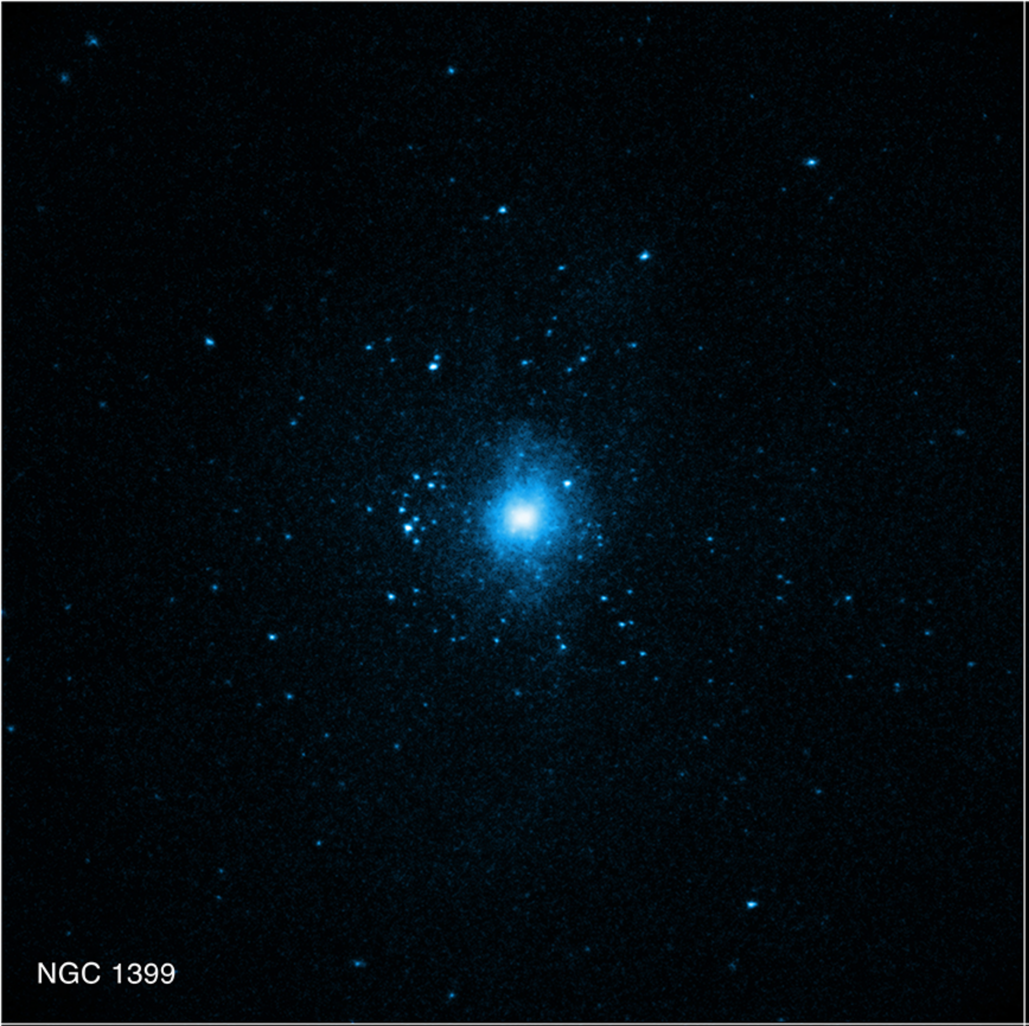
Nardini et al. 2015

Correlation Between Black Hole Mass and Bulge Mass

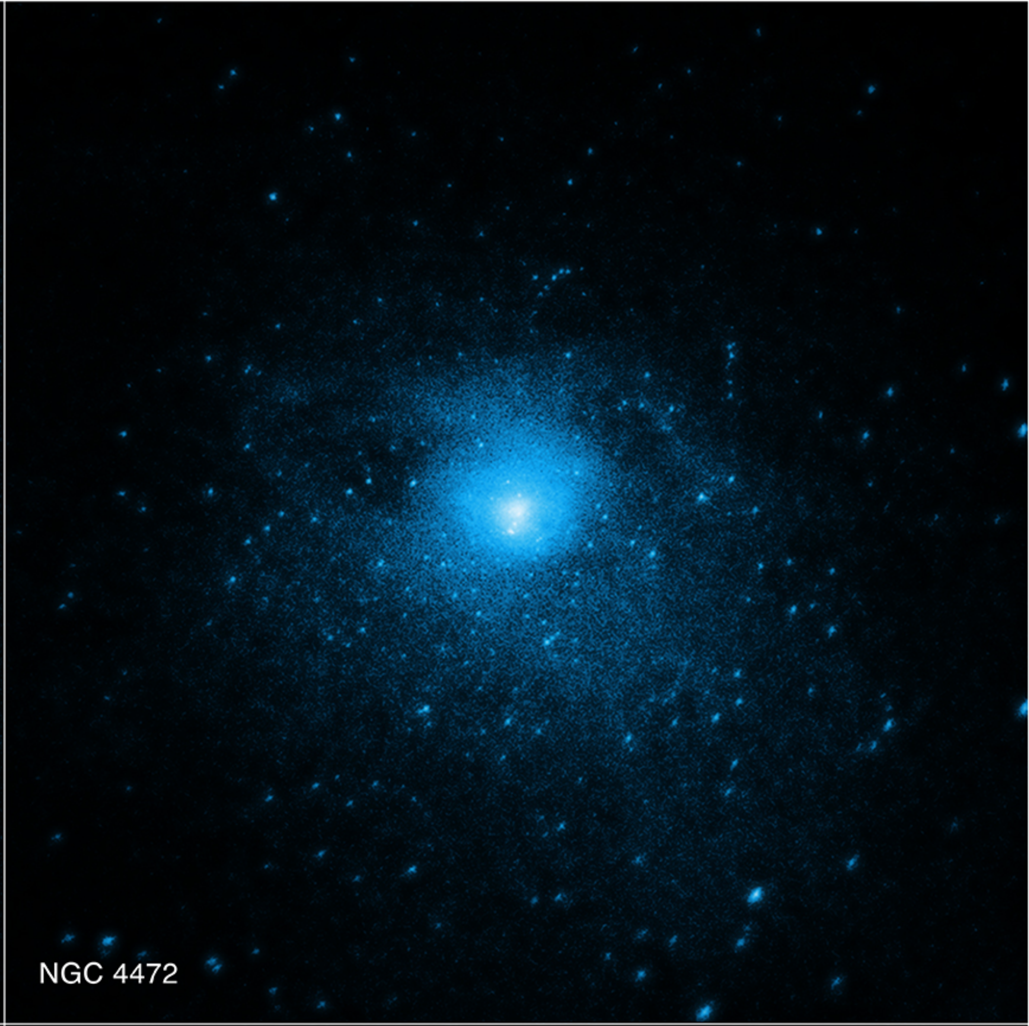



No feedback
SF feedback (no AGN)
SF+AGN (fiducial model)
Star formation feedback
AGN impact
$M_{stellar}$~2×10^{10} $M_\odot$
Semi-empirical relationship (Moster+13)
0.100
0.010
0.001
60%
6%
0.6%
11
12
13
14
15
Log(halo mass) [$M_\odot$]
Stellar mass / halo mass (average)
Baryon to stars conversion efficiency

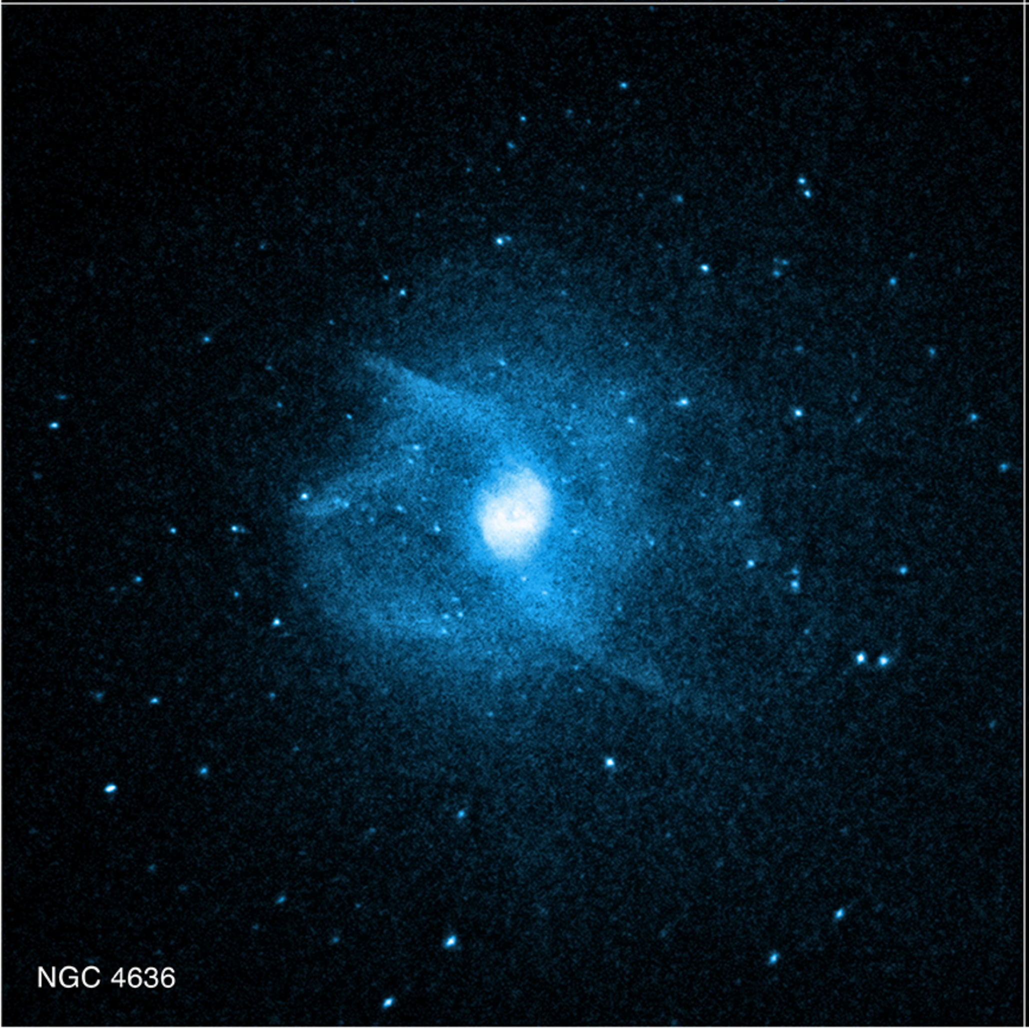
by Robert Gendler



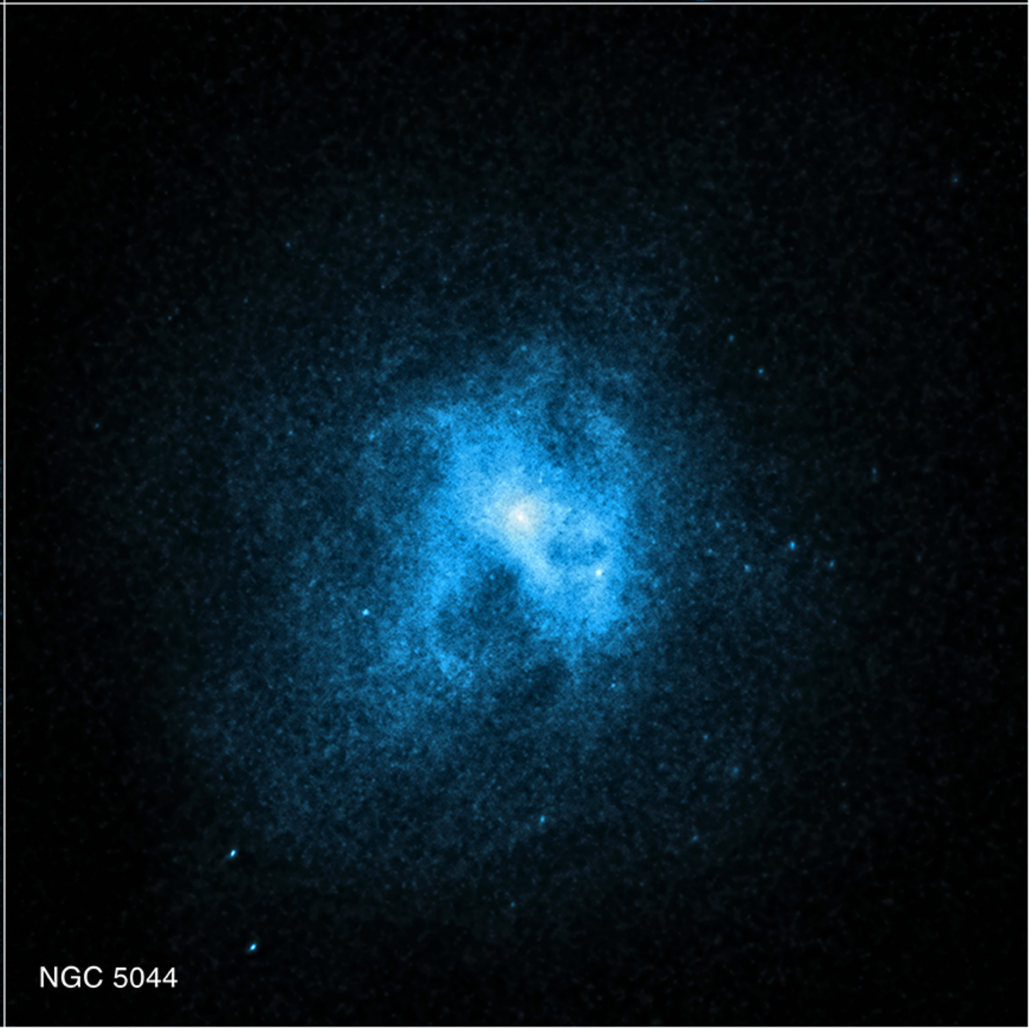
NGC 1399



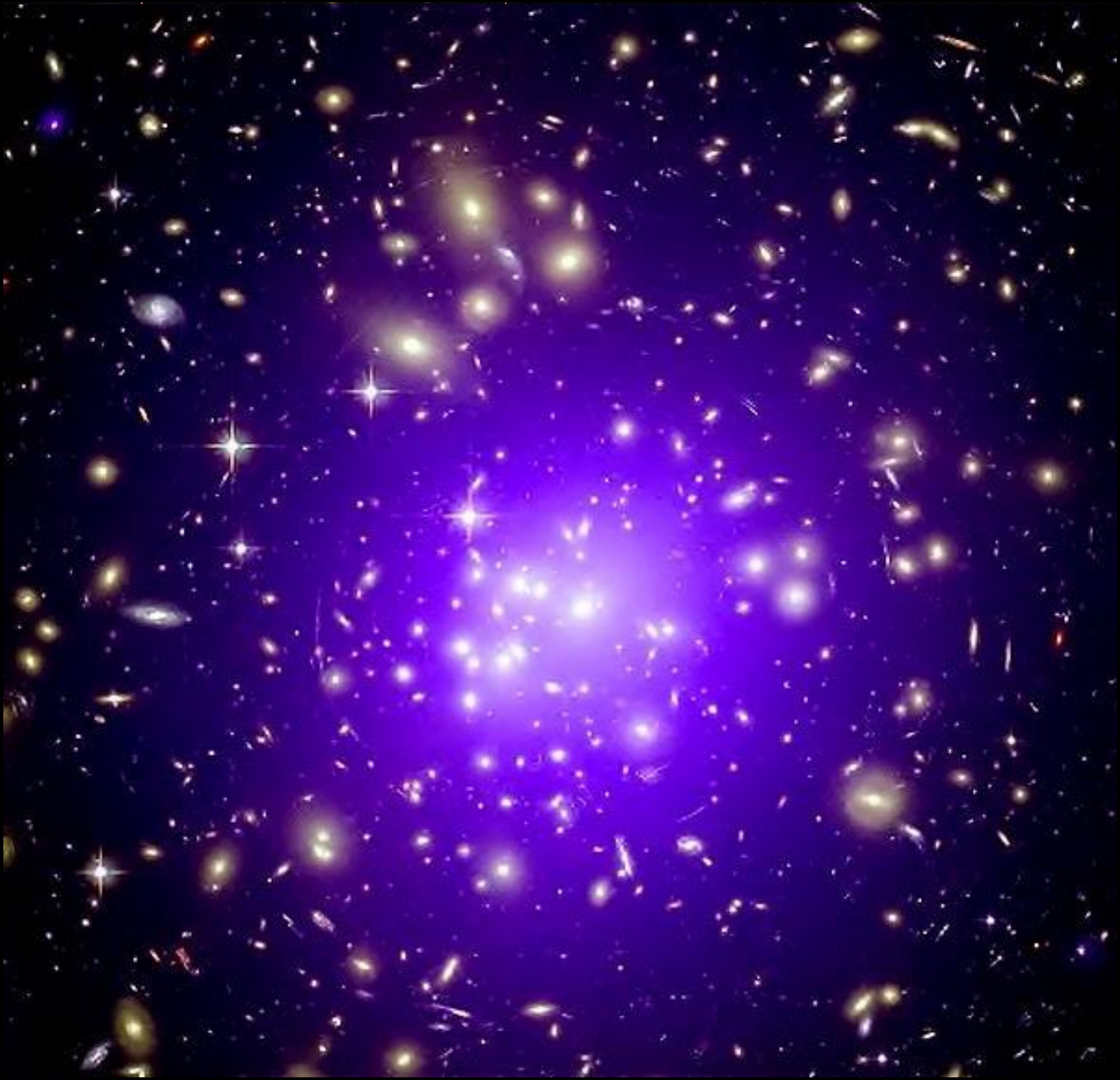
NGC 4472



NGC 4636



NGC 5044

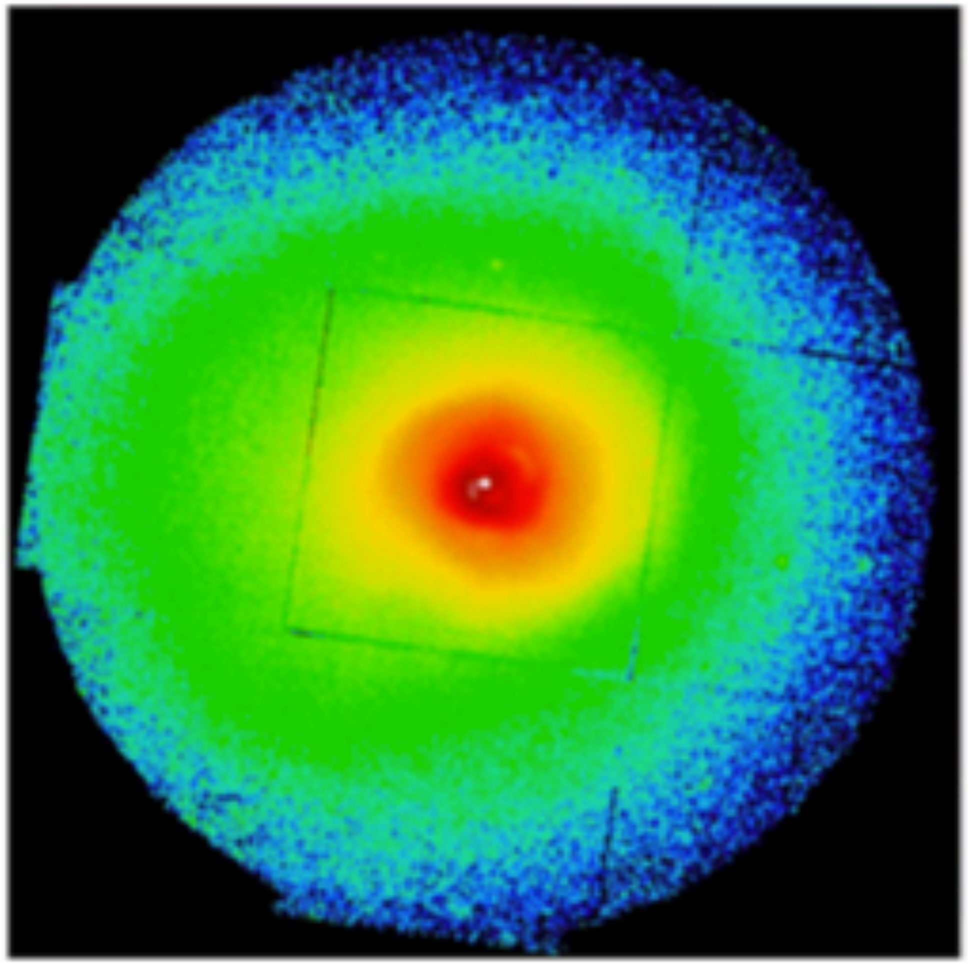


Cooling flows

Cooling time

$$t_{cool} = \frac{\frac{3}{2}nkT}{n^2\Lambda(T)} \approx 5\,10^8 \text{ years}$$

Fastest cooling near the center

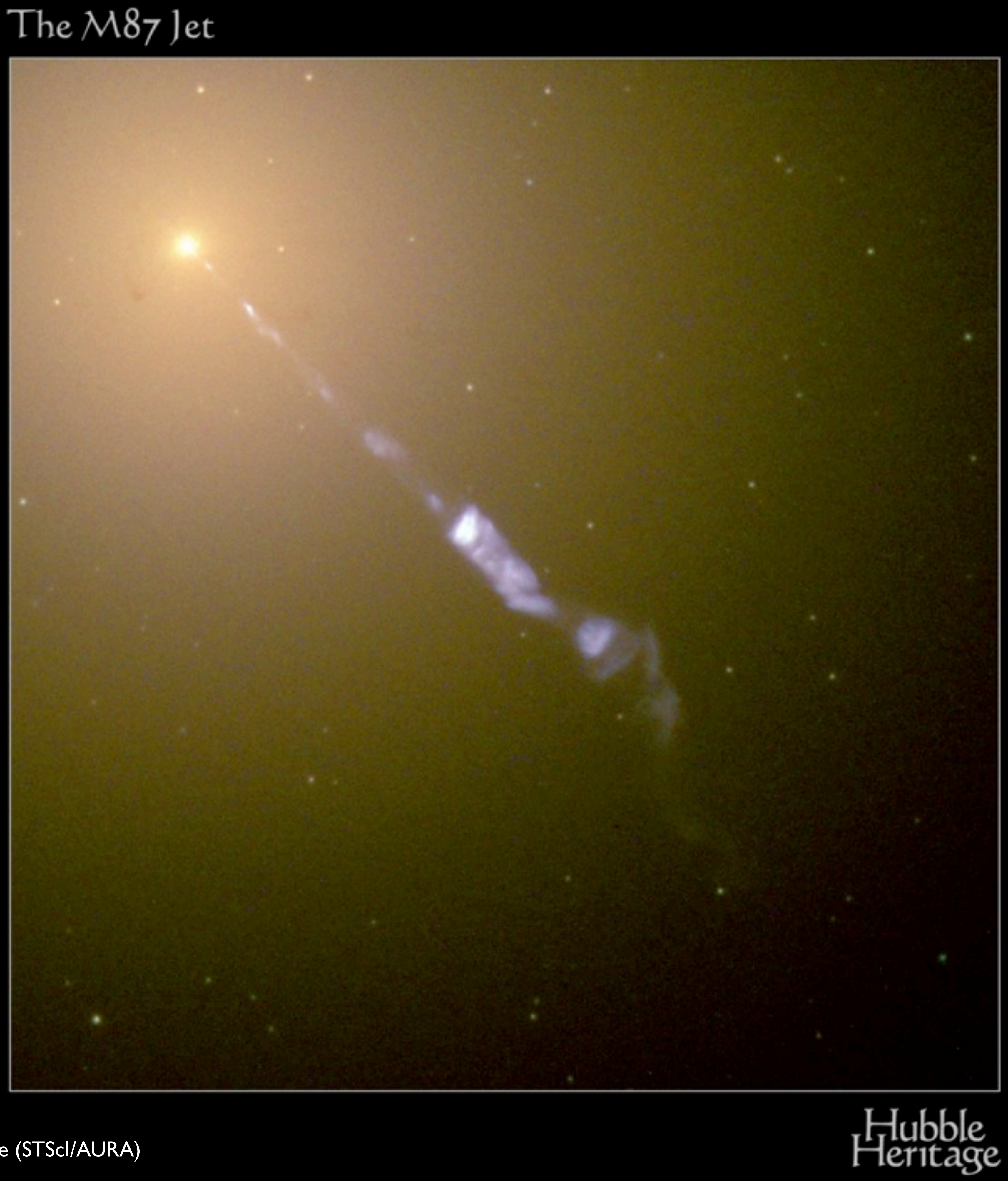


Cooling rate

$$\dot{M} = \frac{L_X}{\frac{3}{2}kT} \times \mu m_p \approx 1000\, M_\odot \text{ yr}^{-1}$$

$(L_X = 10^{45} \text{ erg/s})$

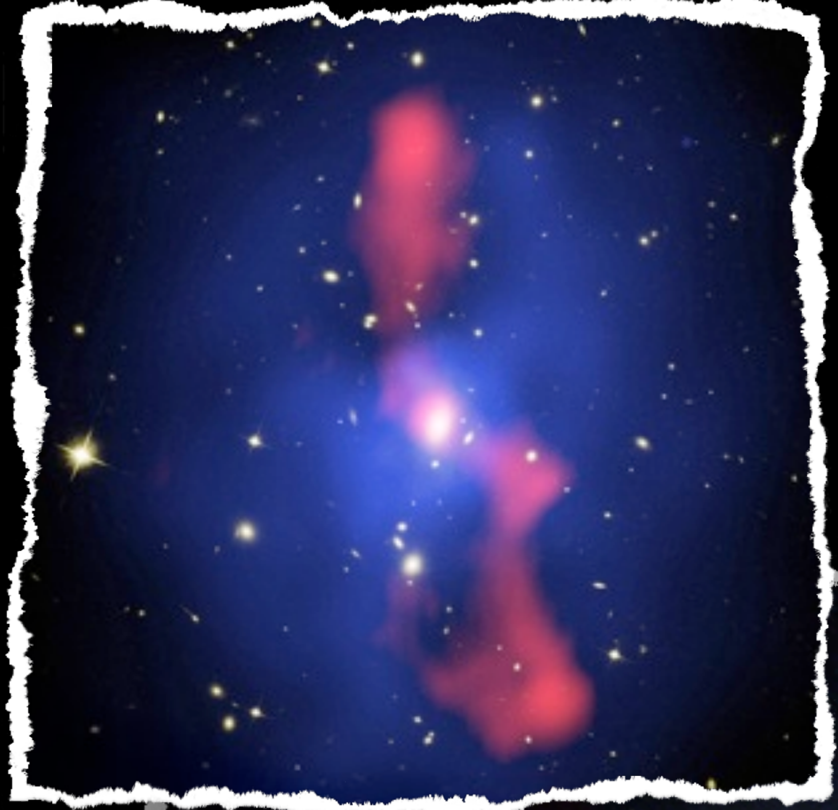
[see Fabian, 1994 for review]



NASA, ESA, Hubble Heritage (STScI/AURA)

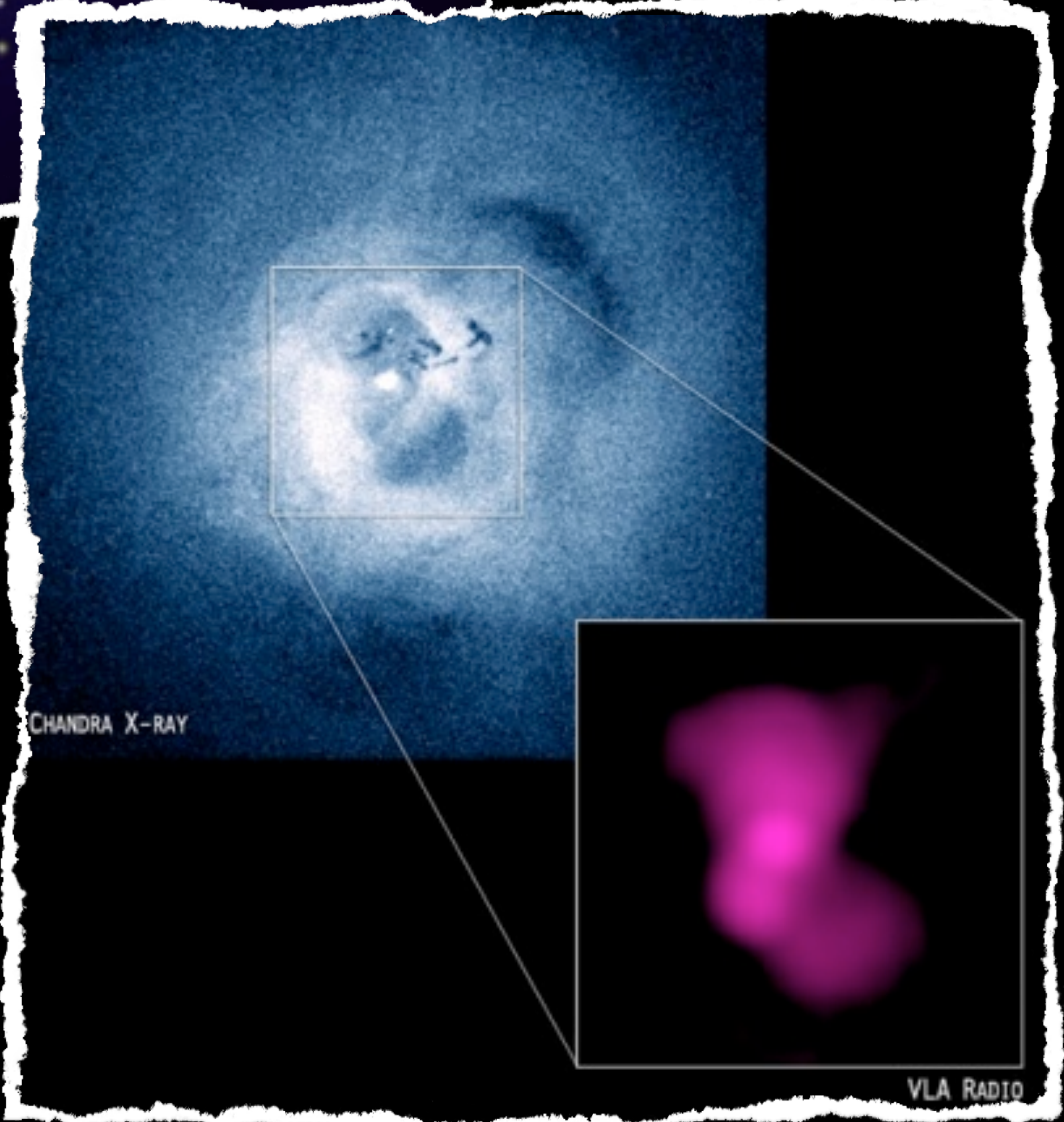
NASA/CXC/A.Hobart

MS0735.6+7421



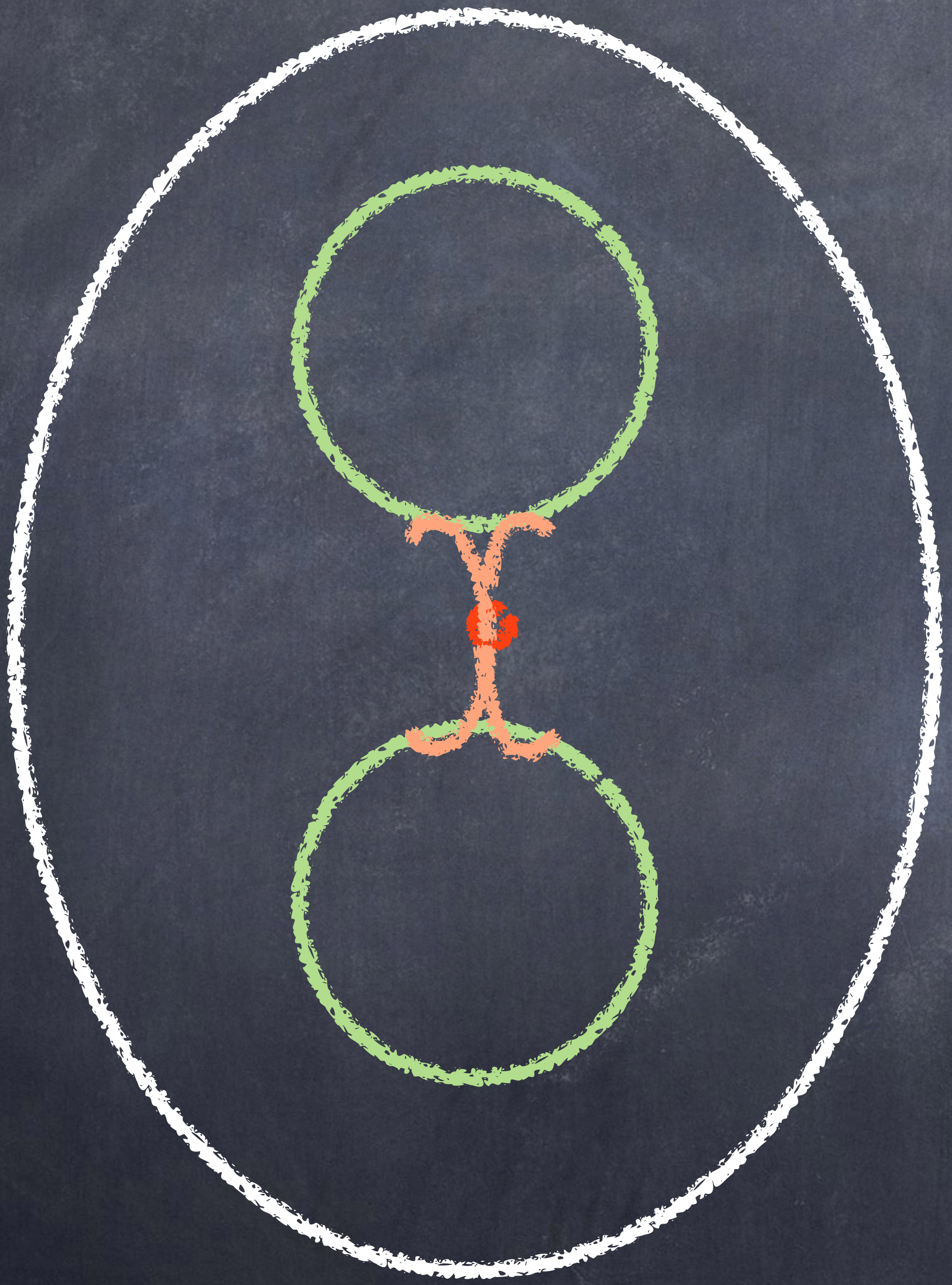
Hydra A

M87 / Virgo



NGC1275 / Perseus

AGN feedback

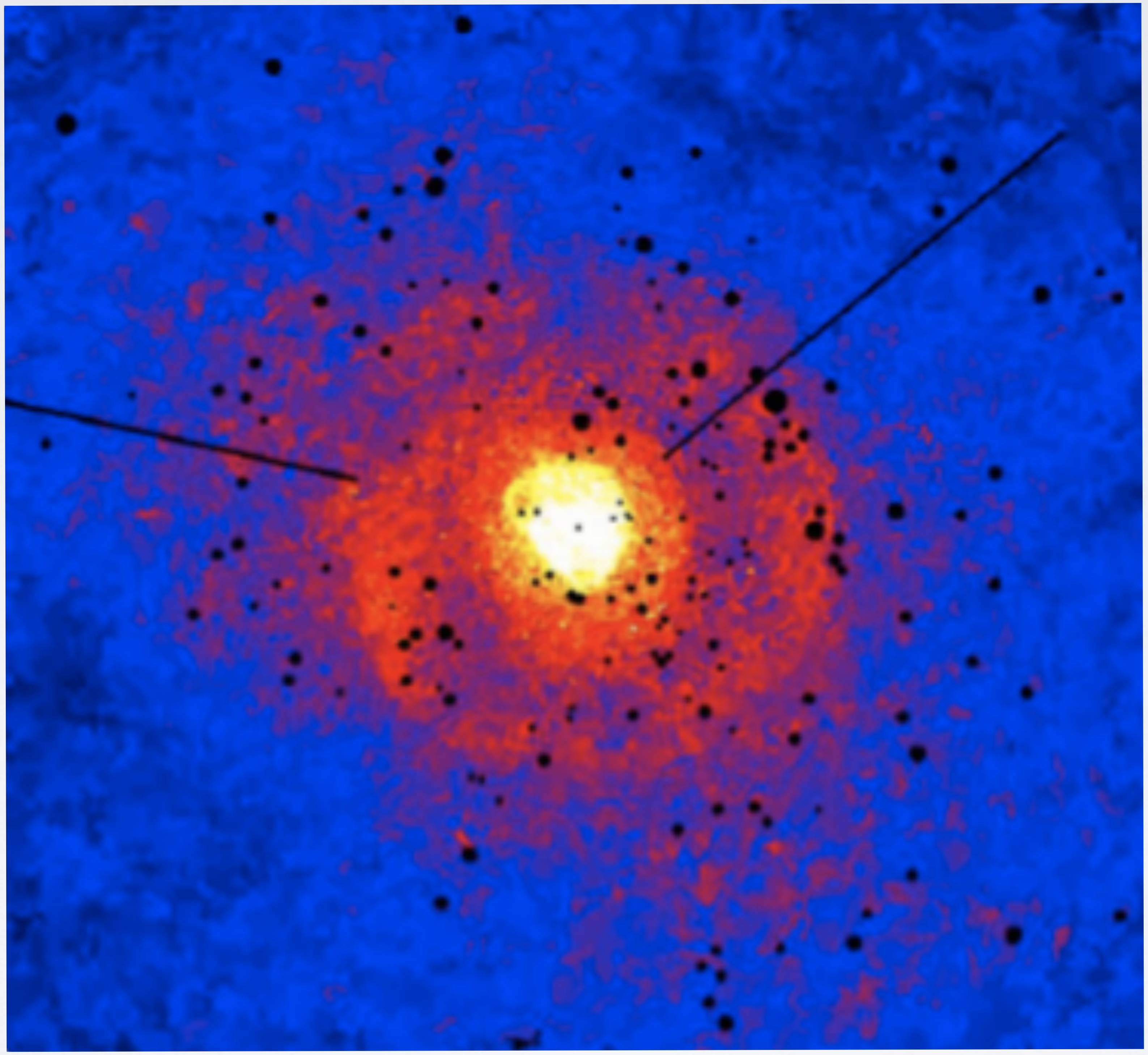


shocks: high temperature; high pressure

cavities: radio bright; X-ray faint

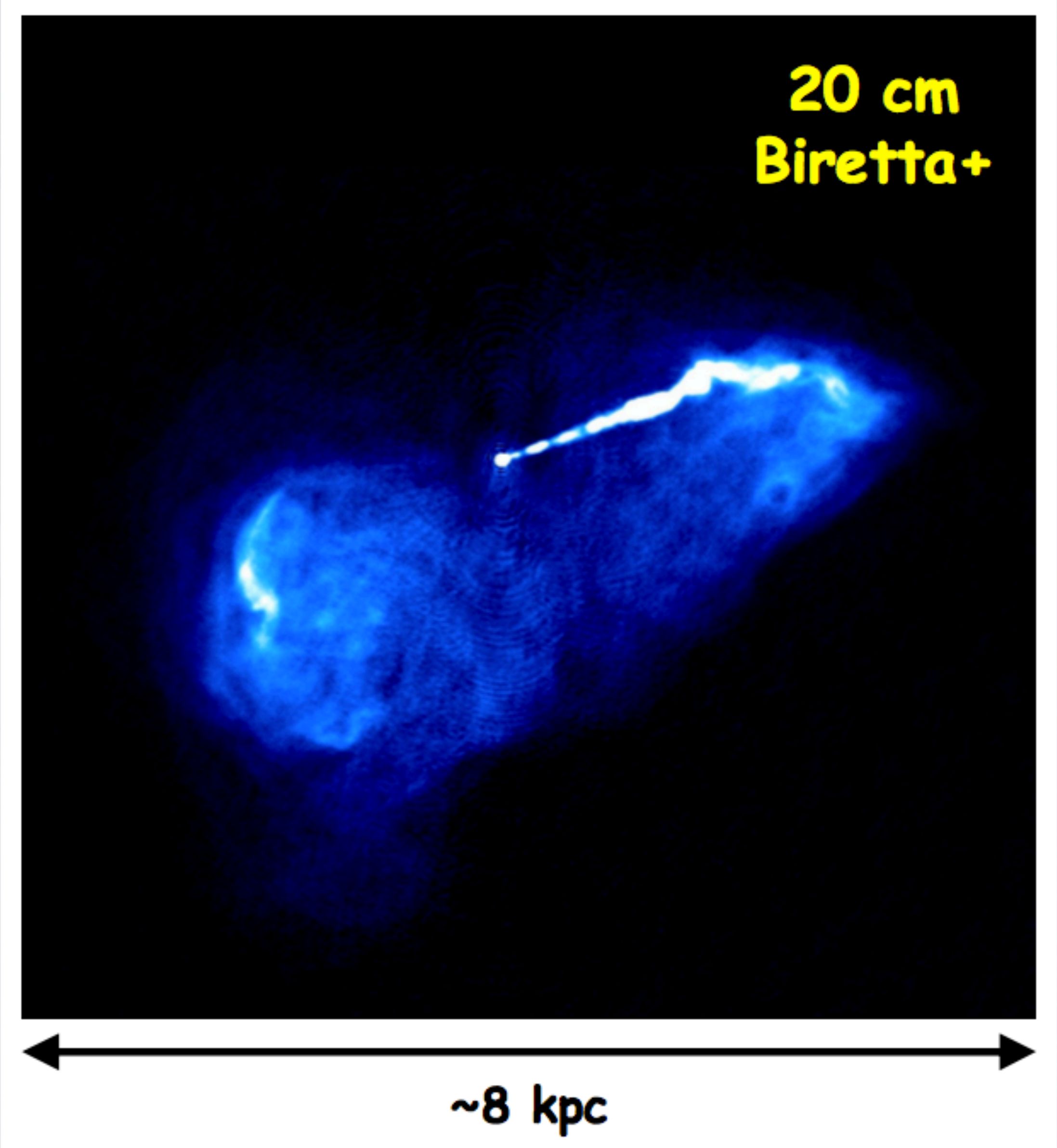
filaments: X-ray bright; low temperature; metal rich

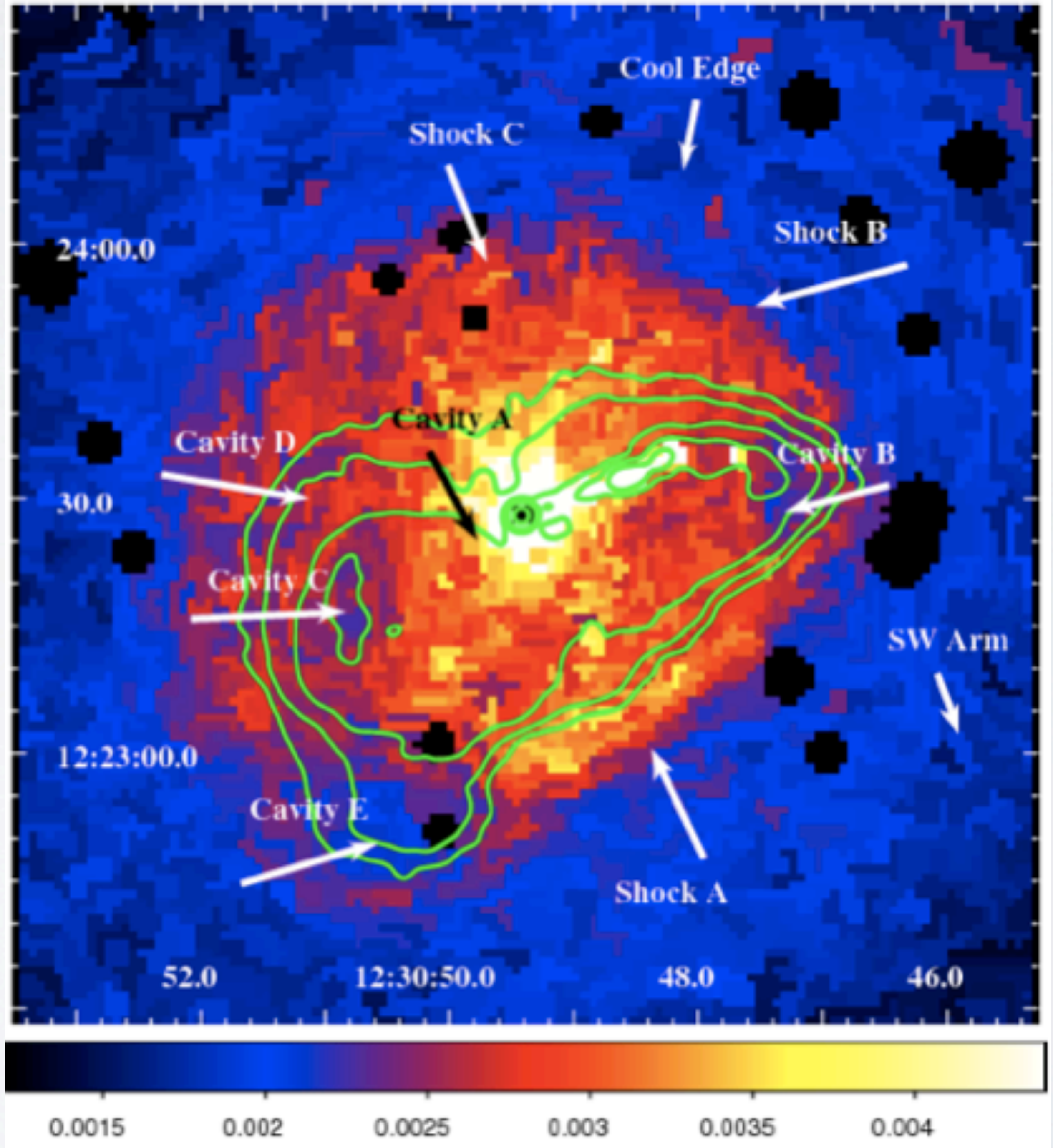
PRESSURE (*nkT*) MAP



Millon et al. 2010

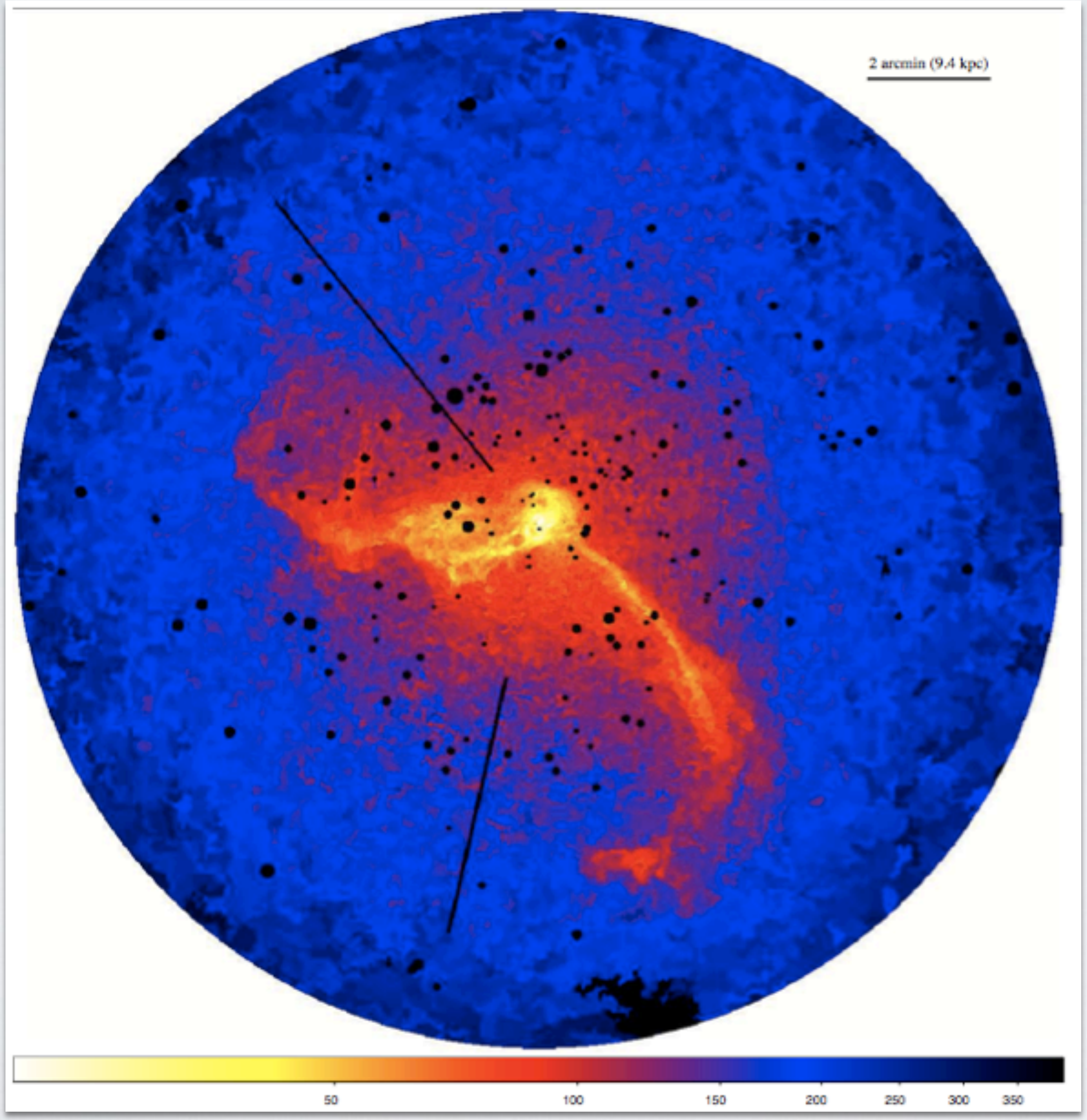
PRESSURE MAP: SPHERICAL SHOCKS





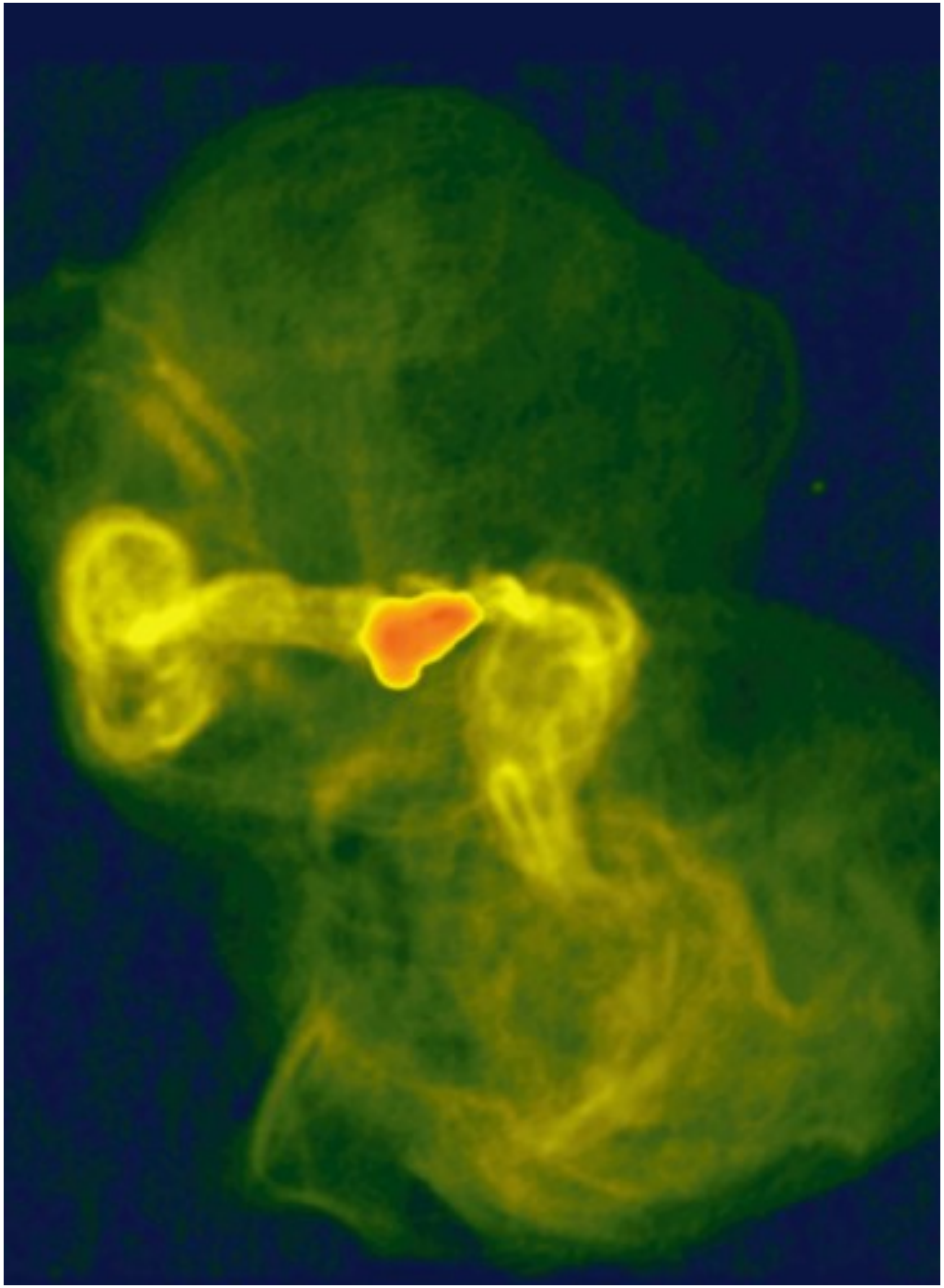
Million et al. 2010

ENTROPY ($kT/n^{2/3}$) MAP

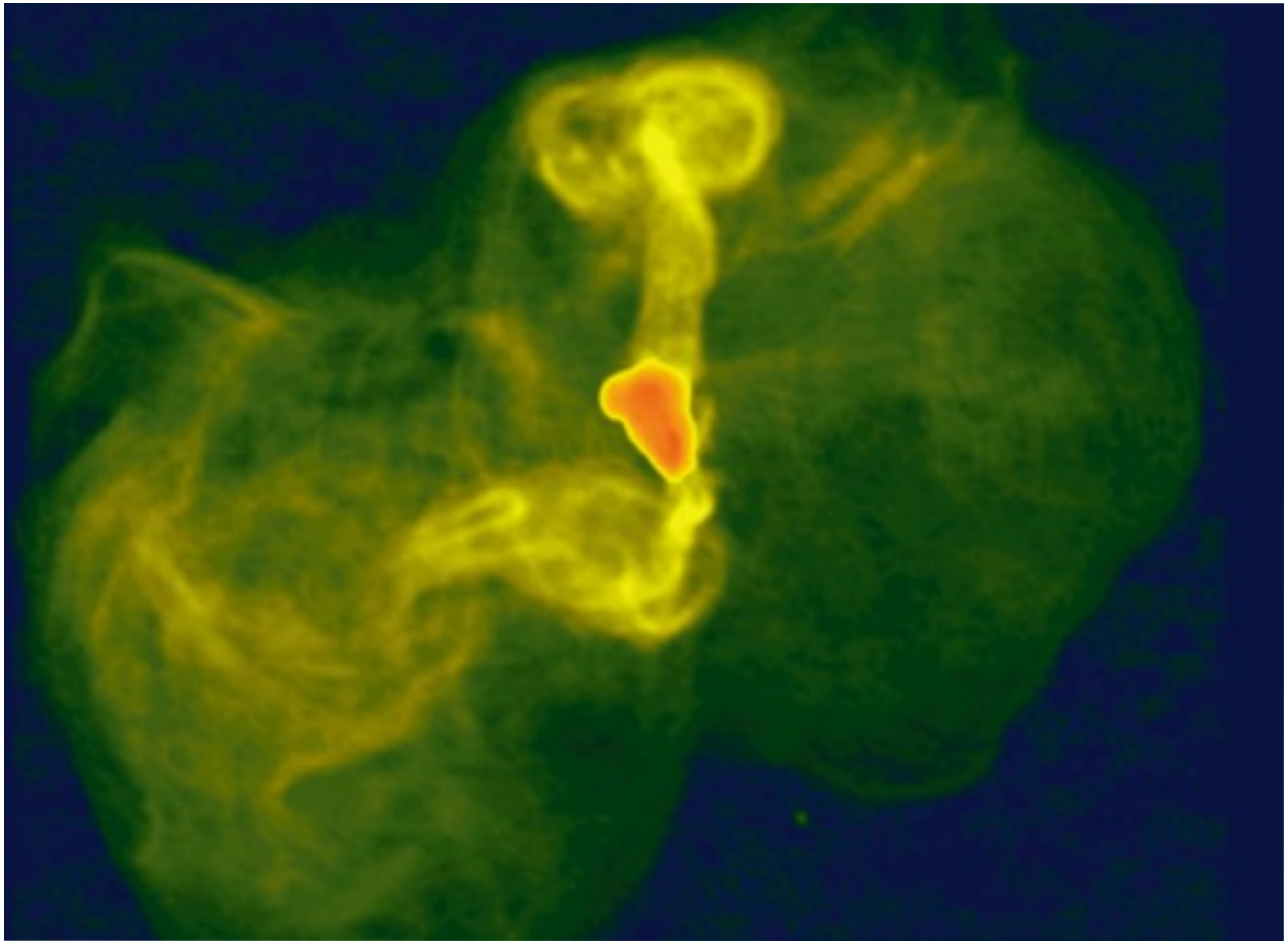


50 100 150 200 250 350

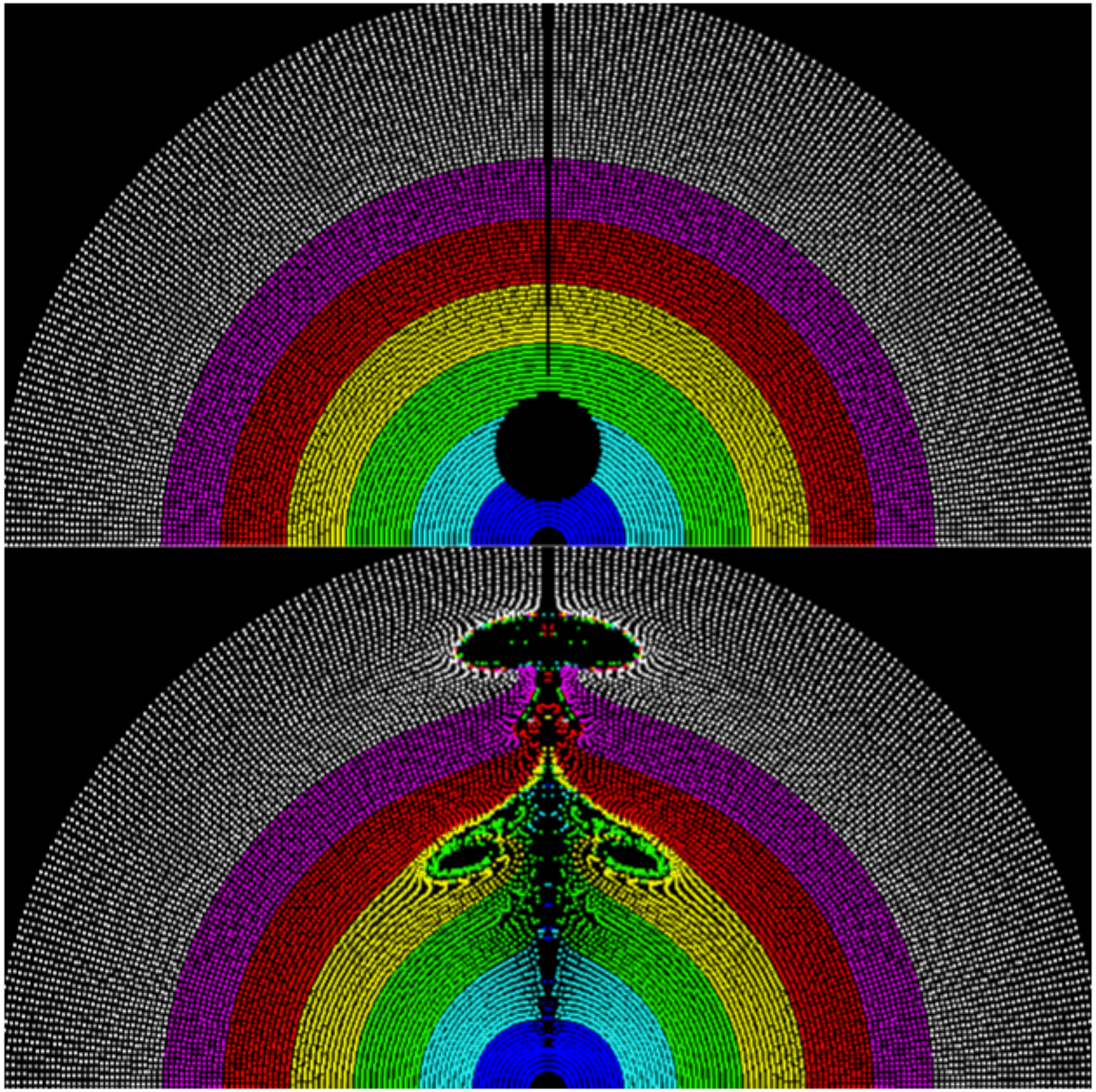
Million et al. 2010



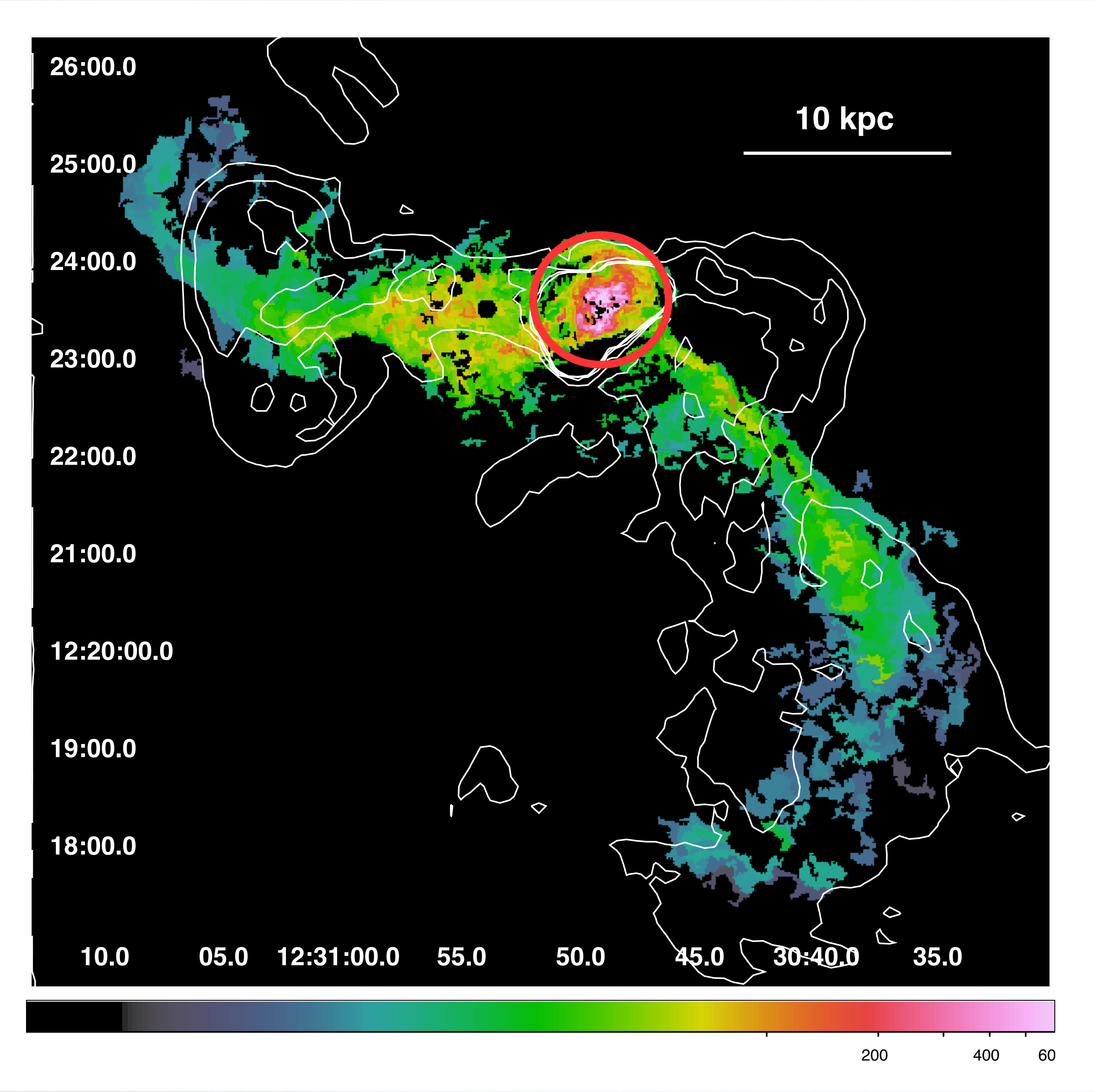
Buoyantly rising relativistic plasma



Entrainment of the cold gas



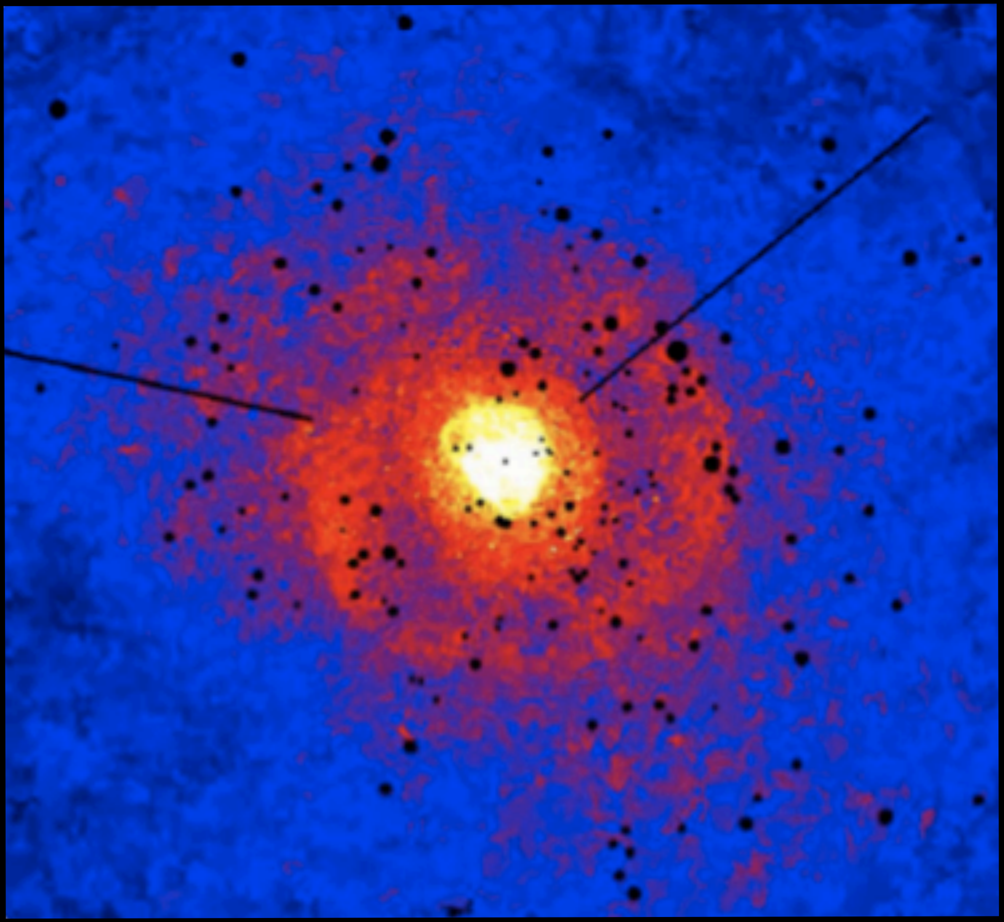
GAS UPLIFT

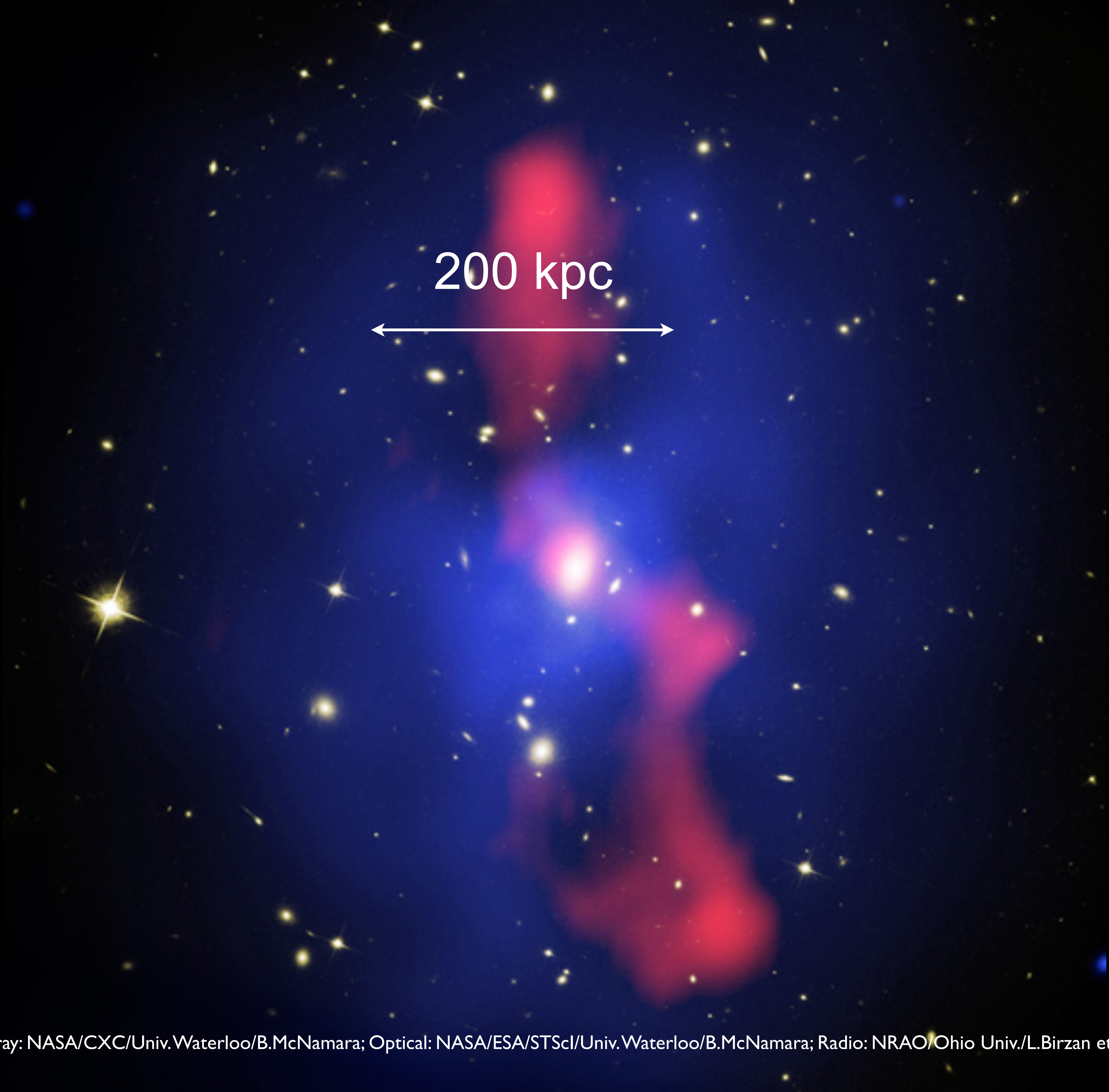


- 6-9x10^8 Msun of gas in arms
- similar to total gas mass within 3.8 kpc radius
- galaxy stripped of its lowest entropy gas
- AGN feedback in action, preventing star formation

Werner et al. 2010

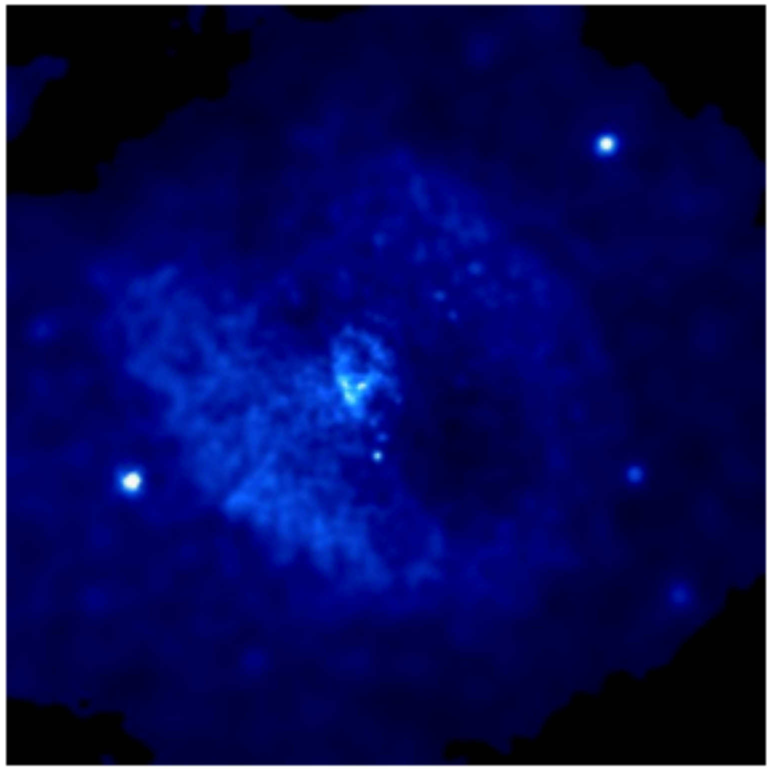
OUTBURSTS NEAR AND FAR



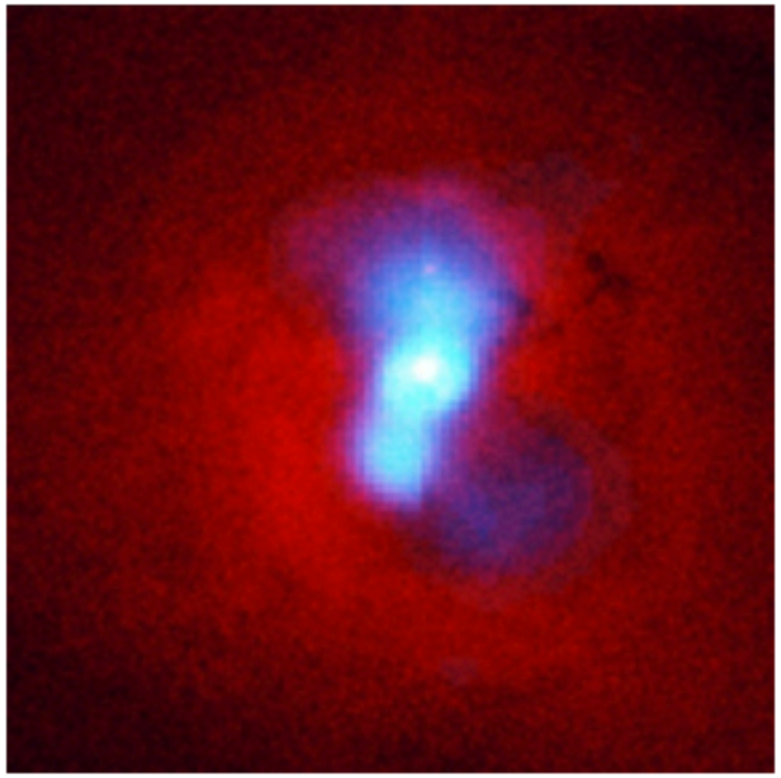


X-ray: NASA/CXC/Univ. Waterloo/B.McNamara; Optical: NASA/ESA/STScI/Univ. Waterloo/B.McNamara; Radio: NRAO/Ohio Univ./L.Birzan et al.

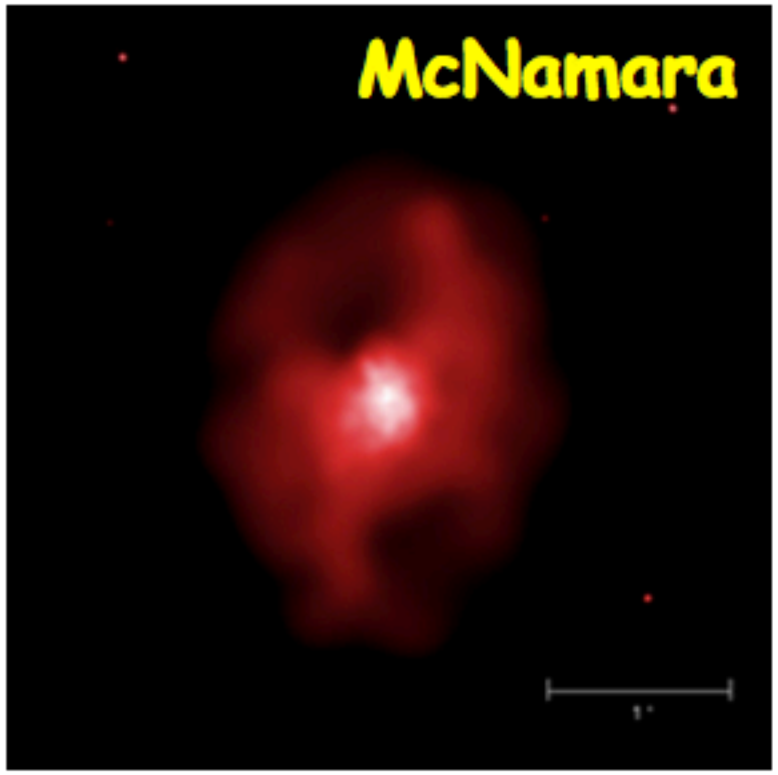
Do we see similar structures in other objects?



1 kpc
10^{56} erg
10^{42} erg/s

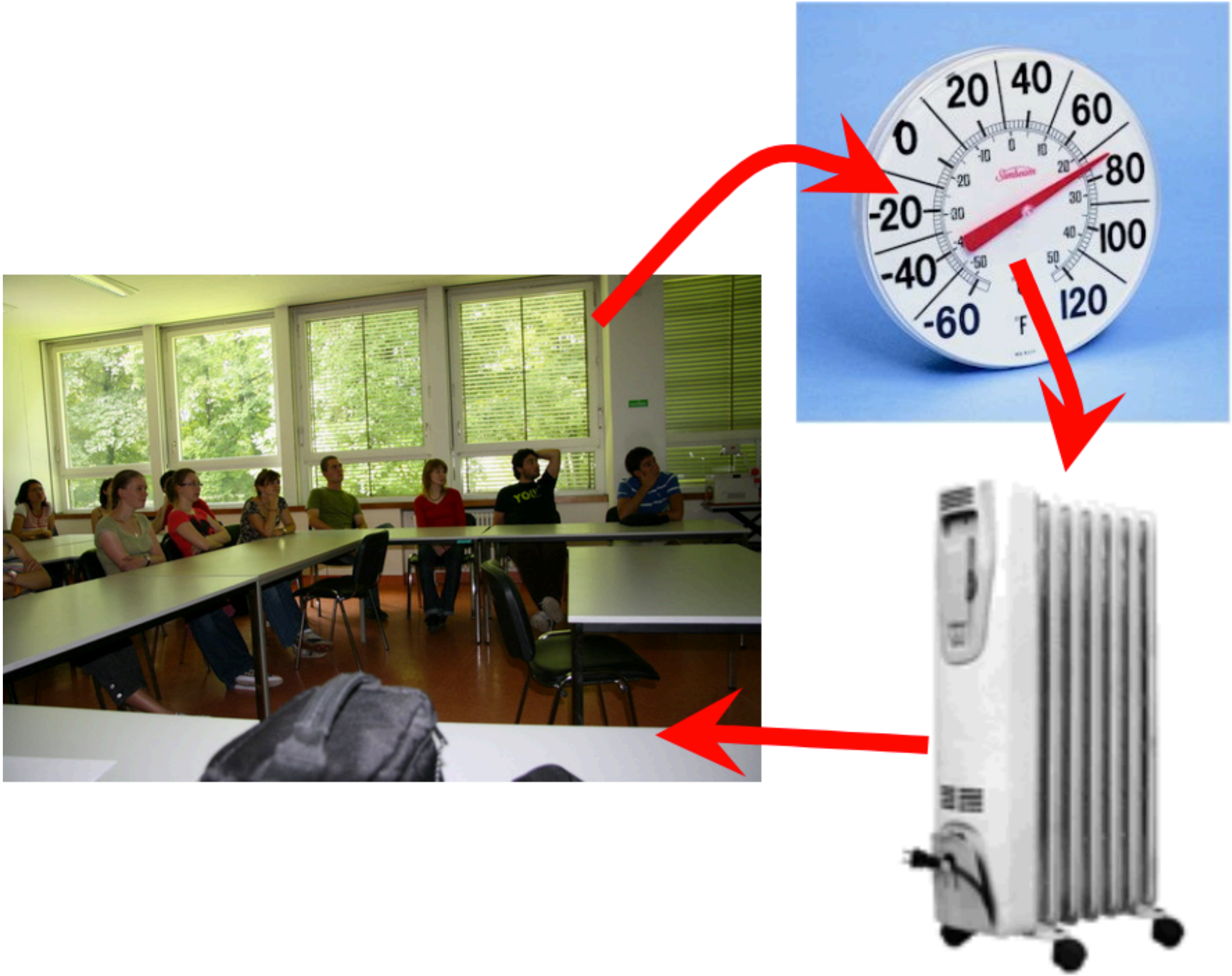


10 kpc
10^{59} erg
10^{45} erg/s

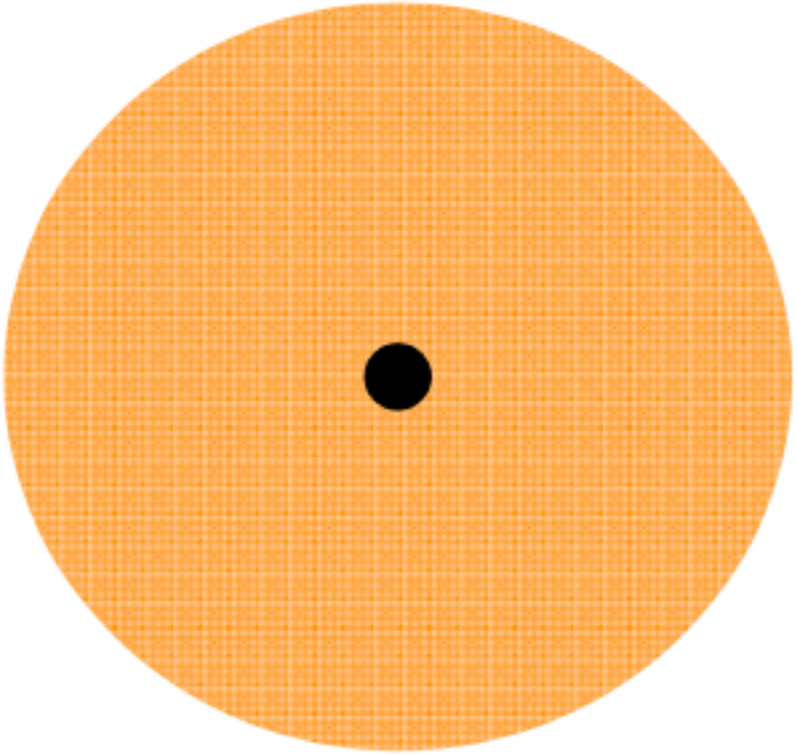


100 kpc
10^{62} erg
10^{46} erg/s

In each object the power provided by SMBH is about right!
How does SMBH know the right power?


20
40
60
0
80
-20
100
-40
120
-60
°F

Spherically symmetric Bondi accretion



$$M, T, \rho$$

$$\frac{GM}{r_b} \approx c_s^2 = \gamma \frac{kT}{\mu m_p}$$

$$r_b = \frac{GM}{c_s^2}$$

$$\dot{M} \approx 4\pi r_b^2 \rho c_s = 4\pi\lambda G^2 M^2 \frac{\rho}{c_s^3}$$

An example of self-regulation of AGN power

$$L_{cooling}$$

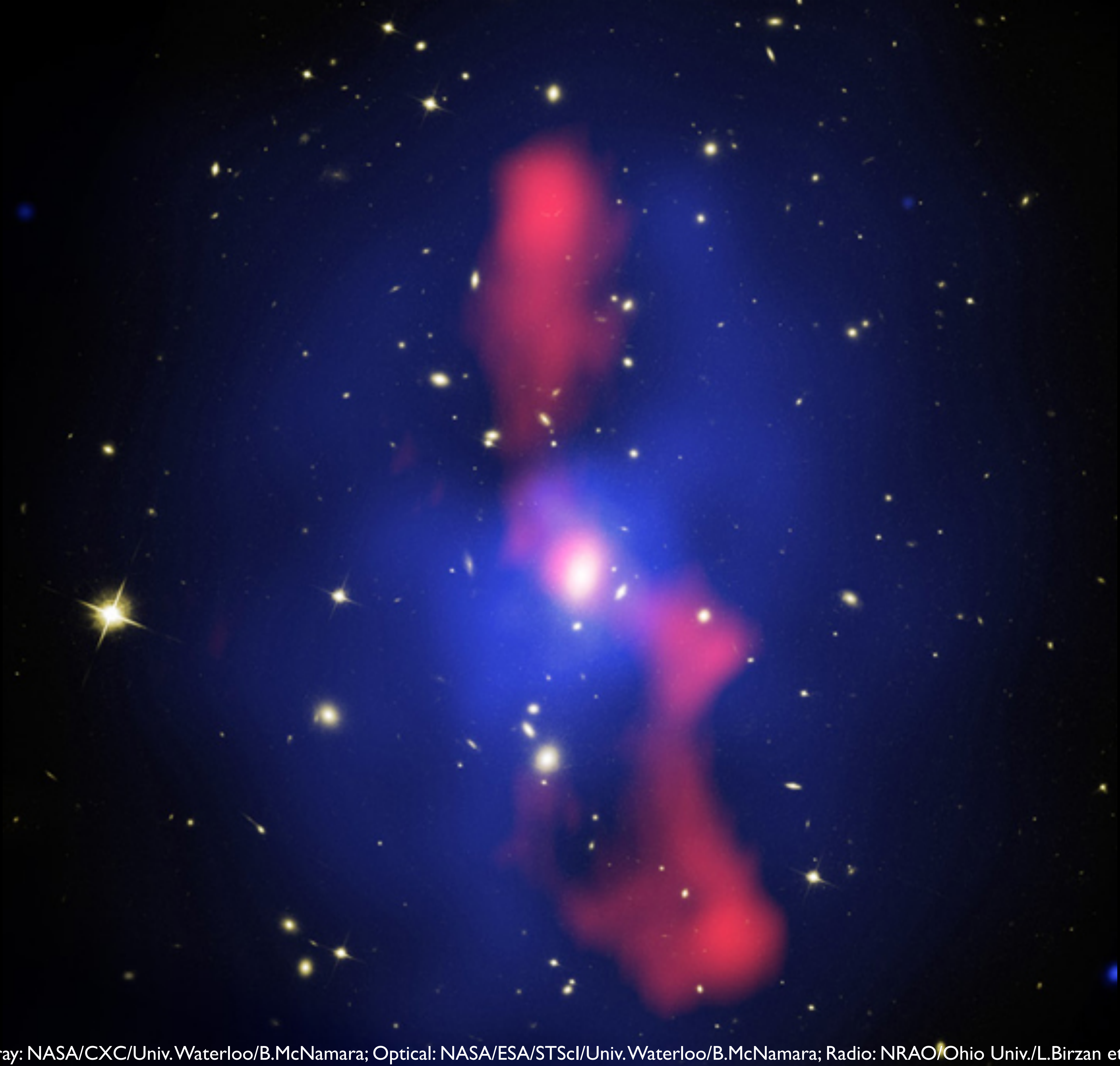
$$L_{jet} \propto \dot{M}_{Bondi} = 4\pi\lambda(GM_{BH})^2 \rho / c_s^3 \propto s^{-3/2}$$

$$L_{jet} > L_{cooling} \Rightarrow s\text{ - increases} \Rightarrow L_{jet}\text{ - decreases}$$

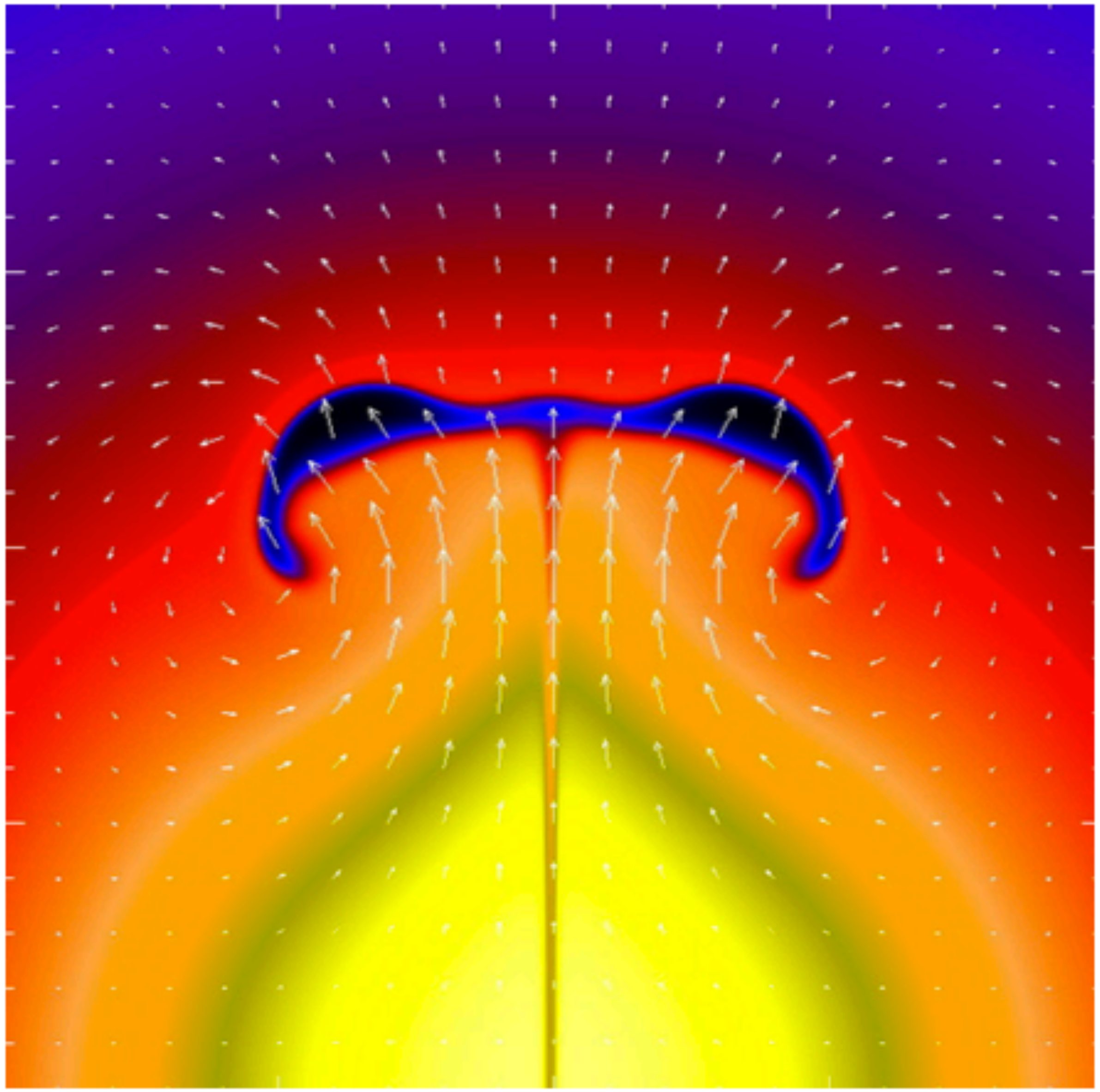
$$L_{jet} < L_{cooling} \Rightarrow s\text{ - decreases} \Rightarrow L_{jet}\text{ - increases}$$

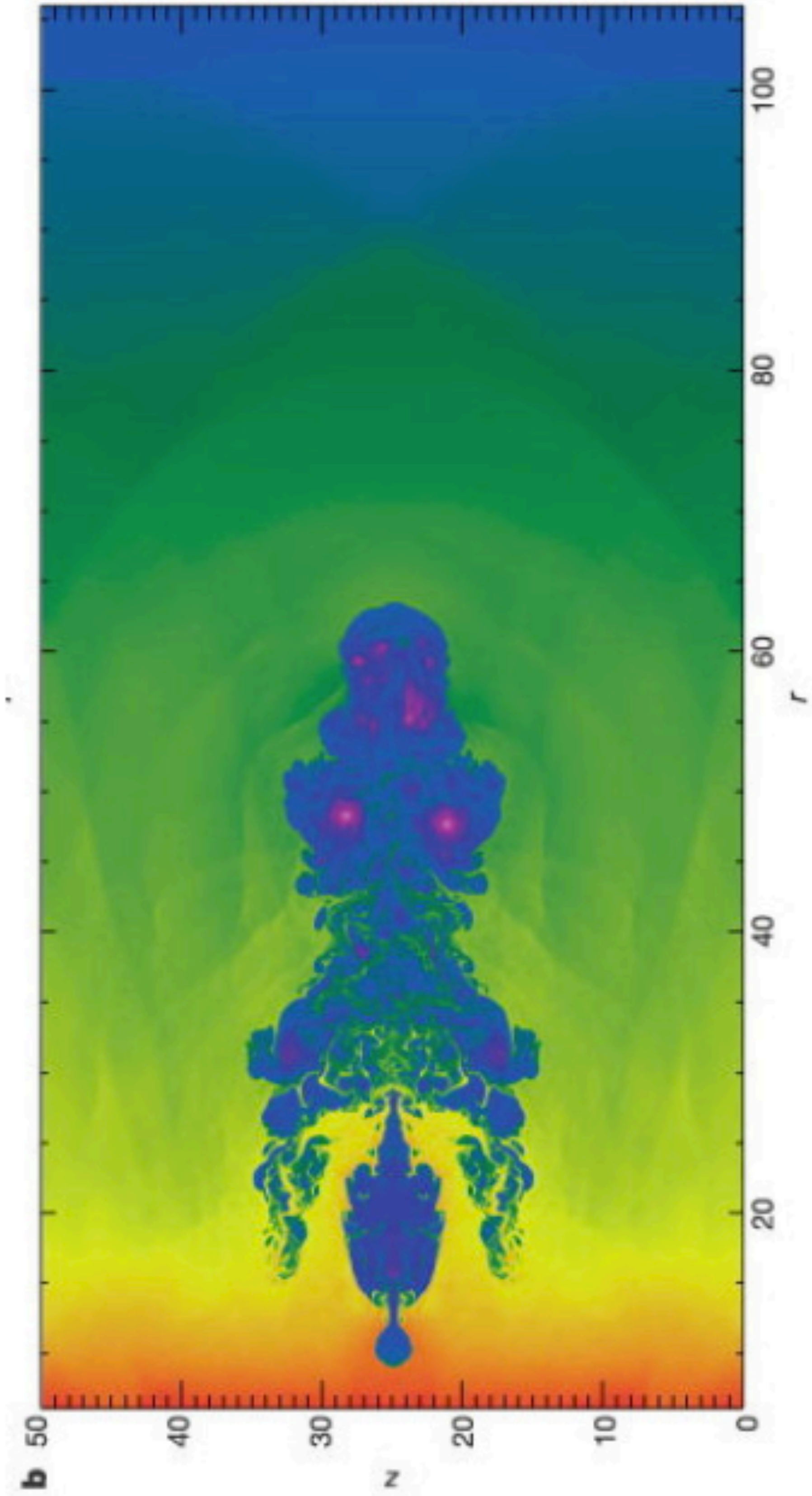
1. System with negative feedback (self-regulated)
2. Stable equilibrium is possible

But what about actual heating mechanism?



X-ray: NASA/CXC/Univ. Waterloo/B.McNamara; Optical: NASA/ESA/STScI/Univ. Waterloo/B.McNamara; Radio: NRAO/Ohio Univ./L.Birzan et al.

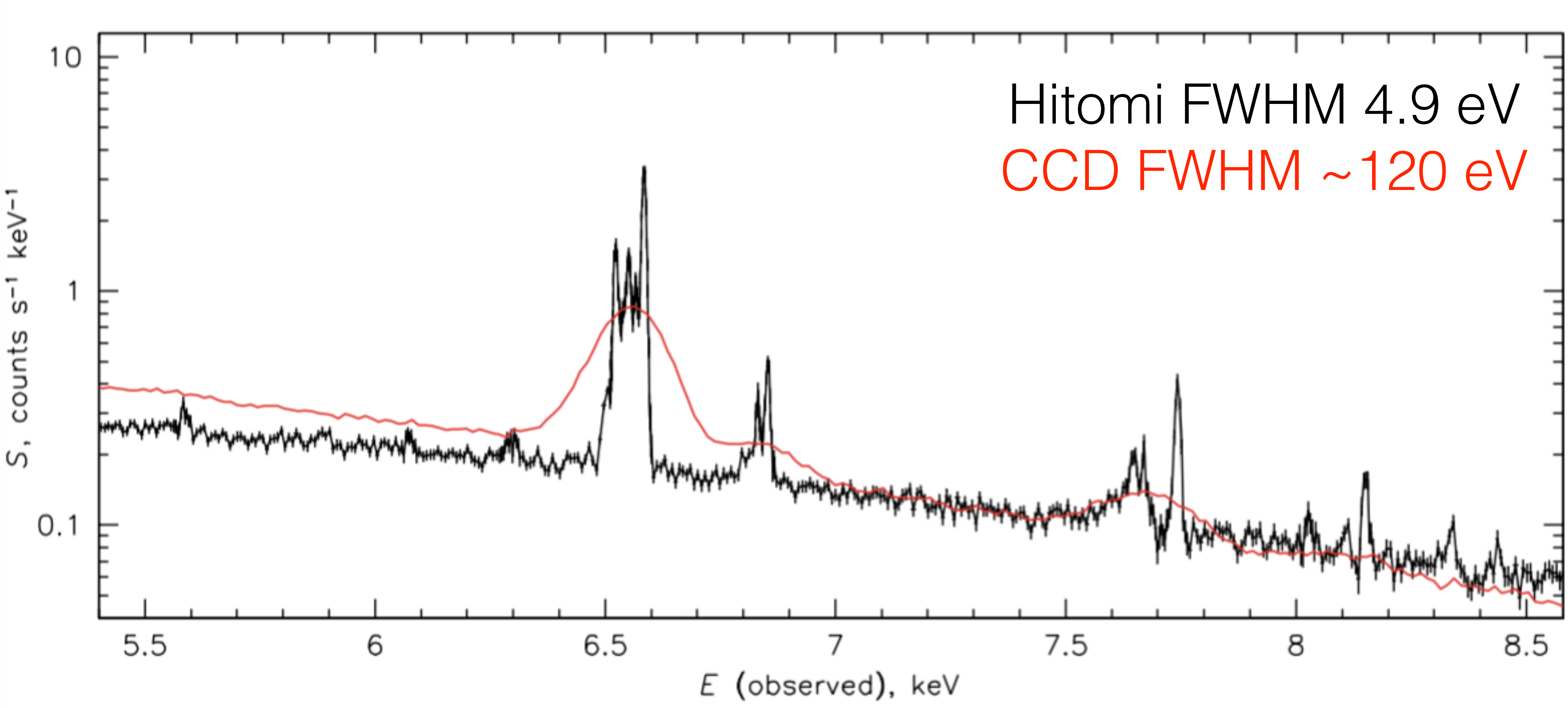




Raising bubbles induce gas motions which eventually dissipate into heat.

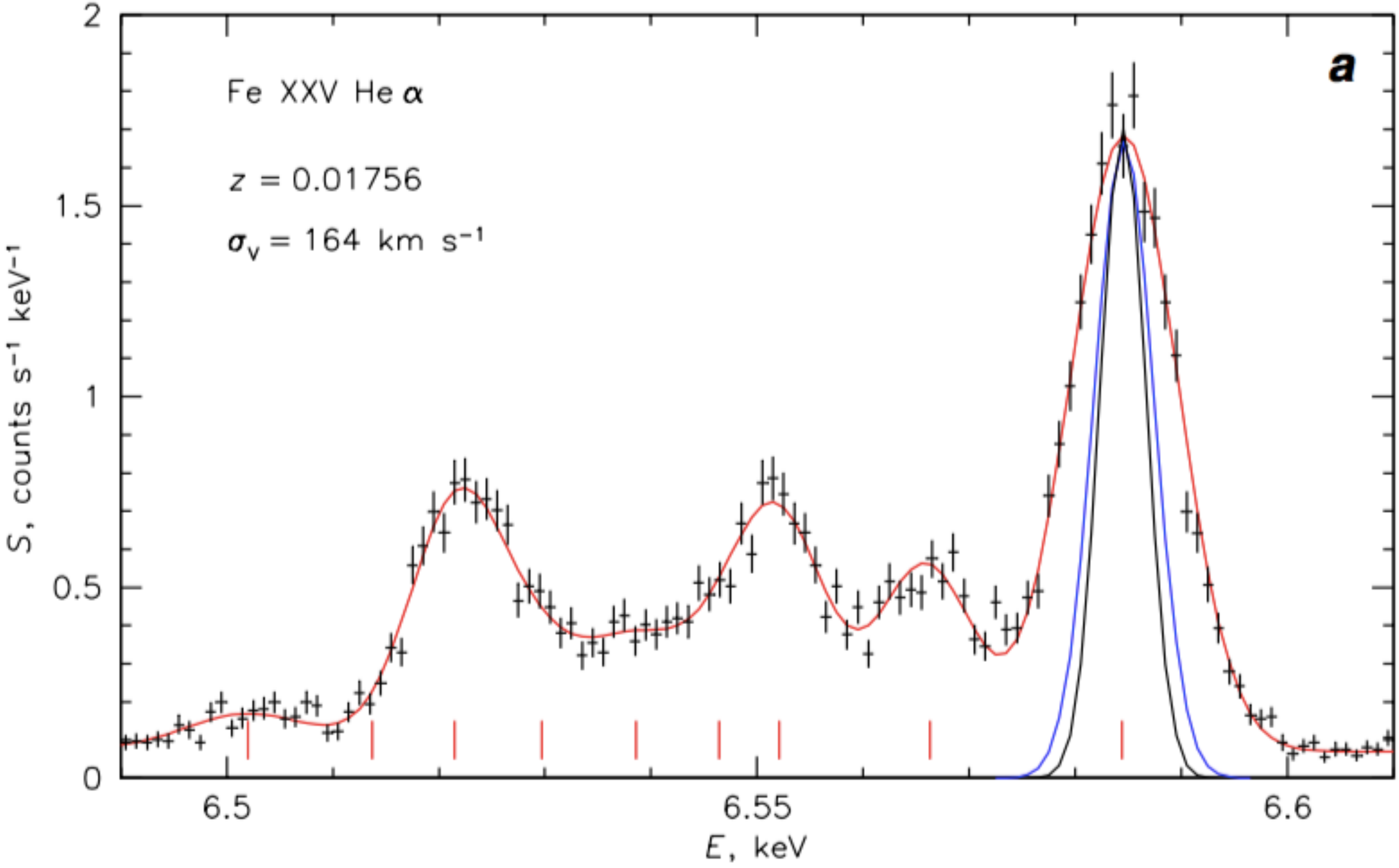
First Hitomi (ASTRO-H) Observation

Resolved X-ray spectrum of the core of Perseus cluster

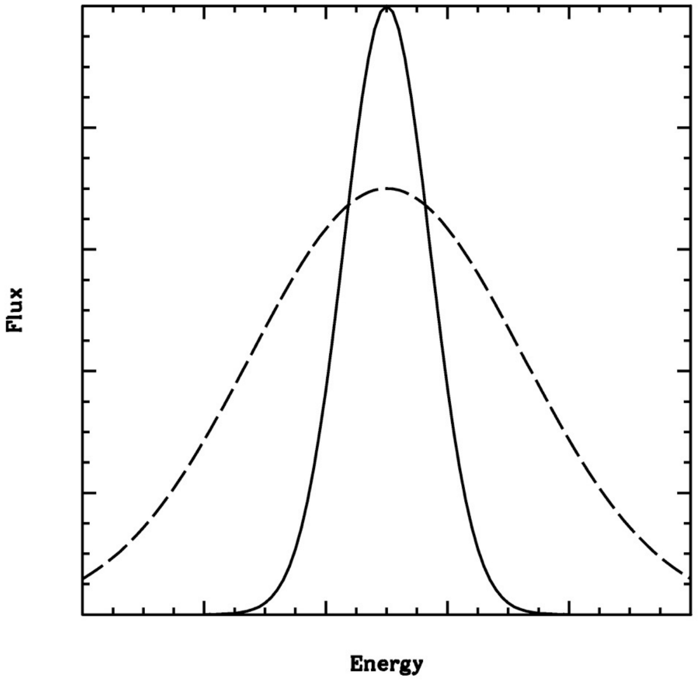


[on behalf of Astro-H collaboration, Takahashi+16, Nature, submitted]

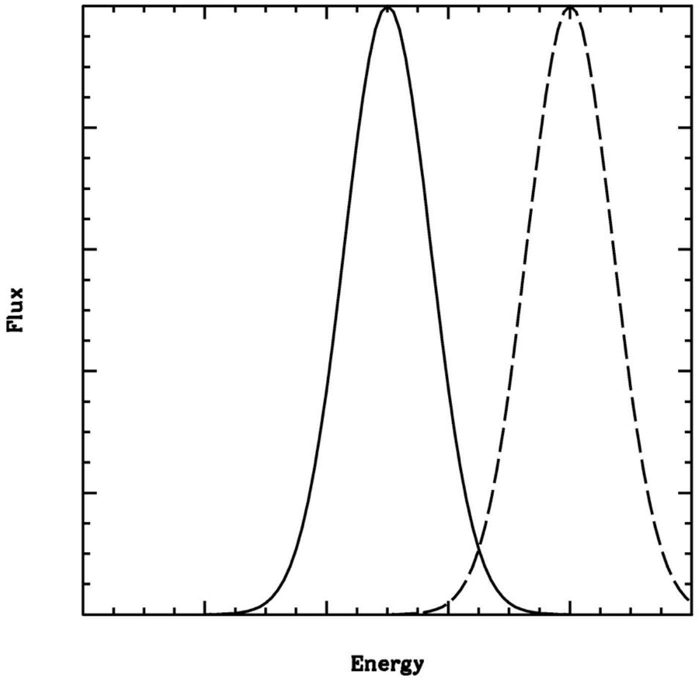
Velocity broadening



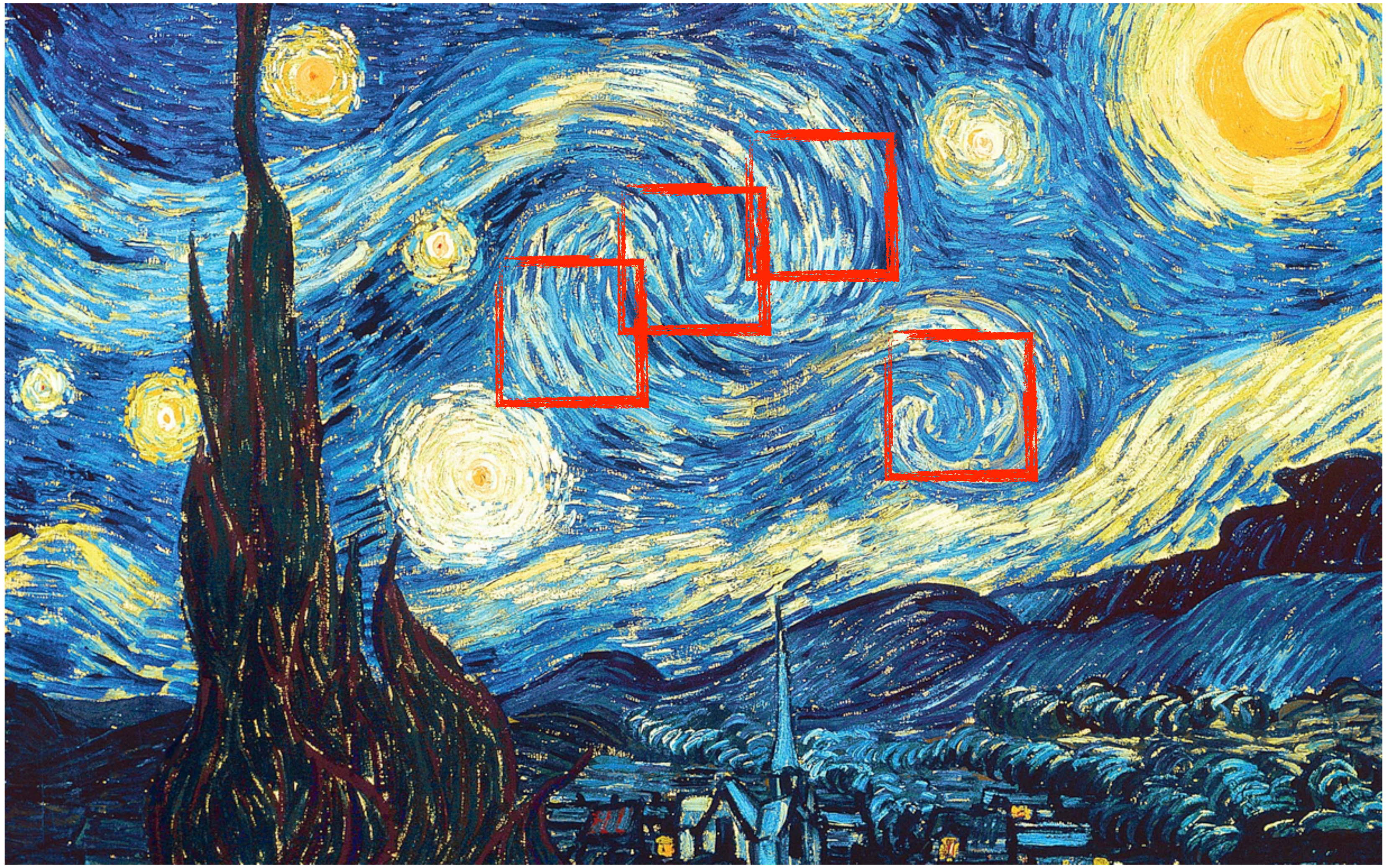
Turbulent and bulk motions



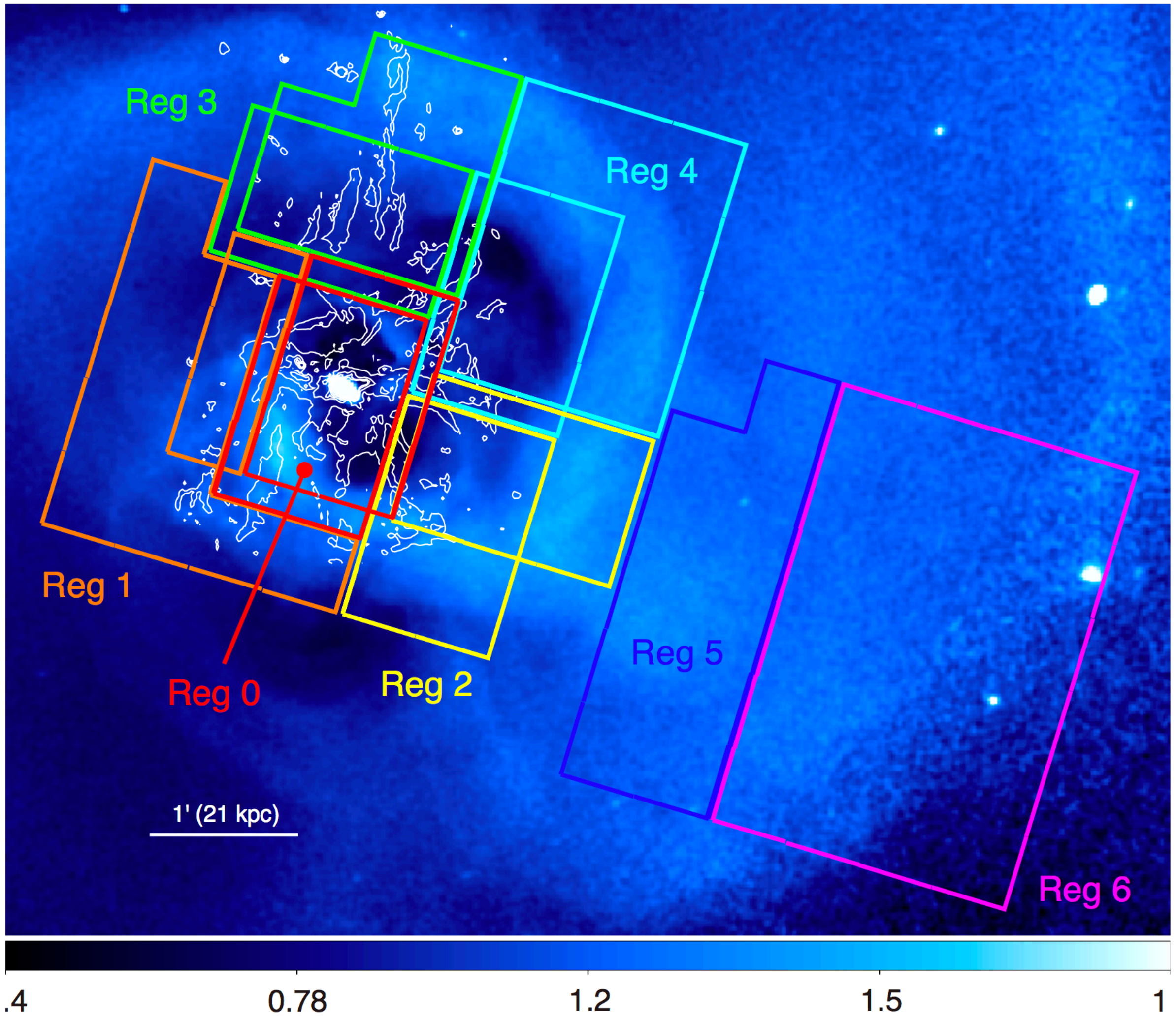
for gas motions on small spatial scales we expect significant line-of-sight velocity dispersion σ, resulting in line broadening, but no centroid shifts



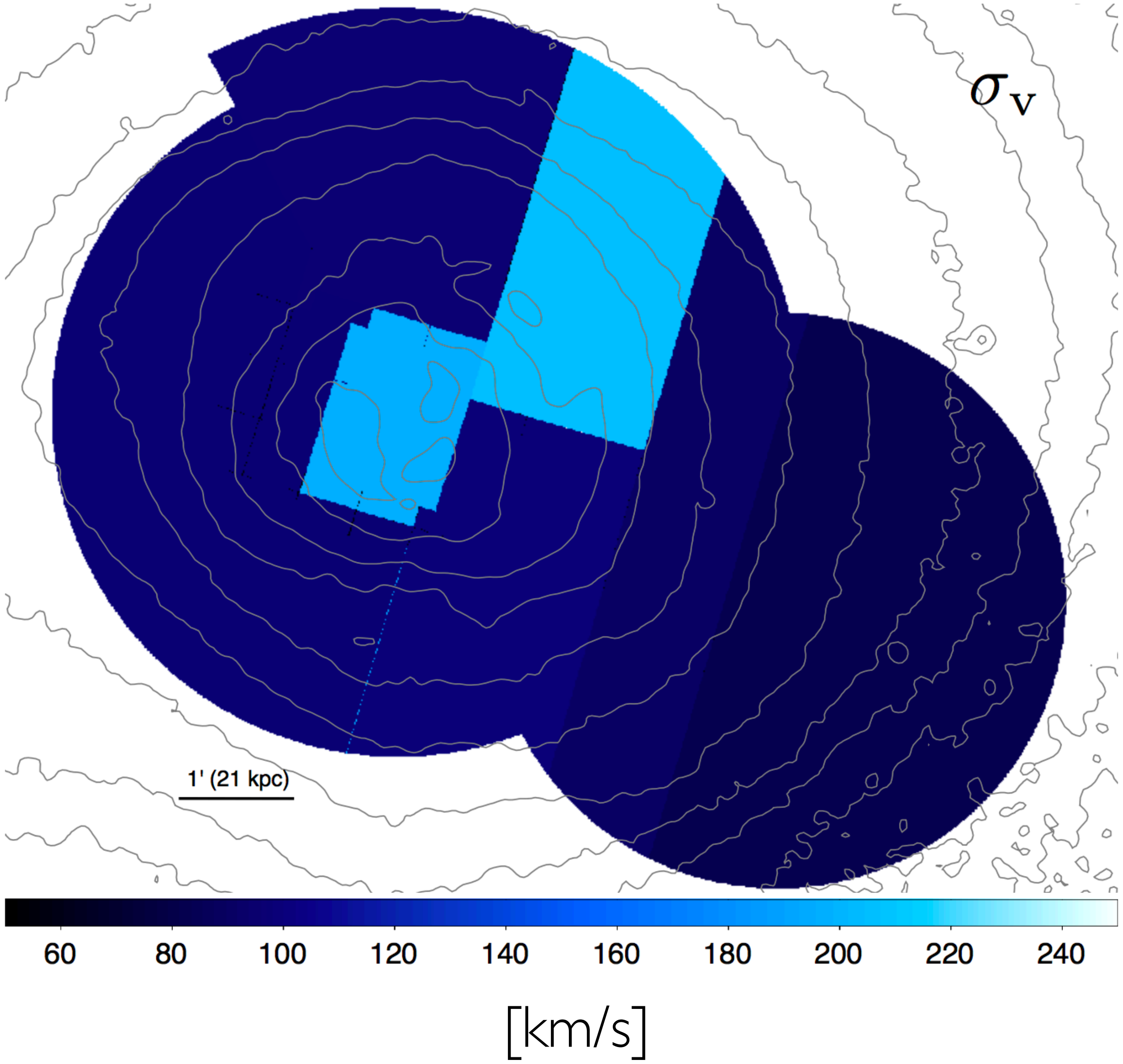
if the spatial scale of motions is large, then we expect significant centroid shifts



First Direct Velocity Measurements

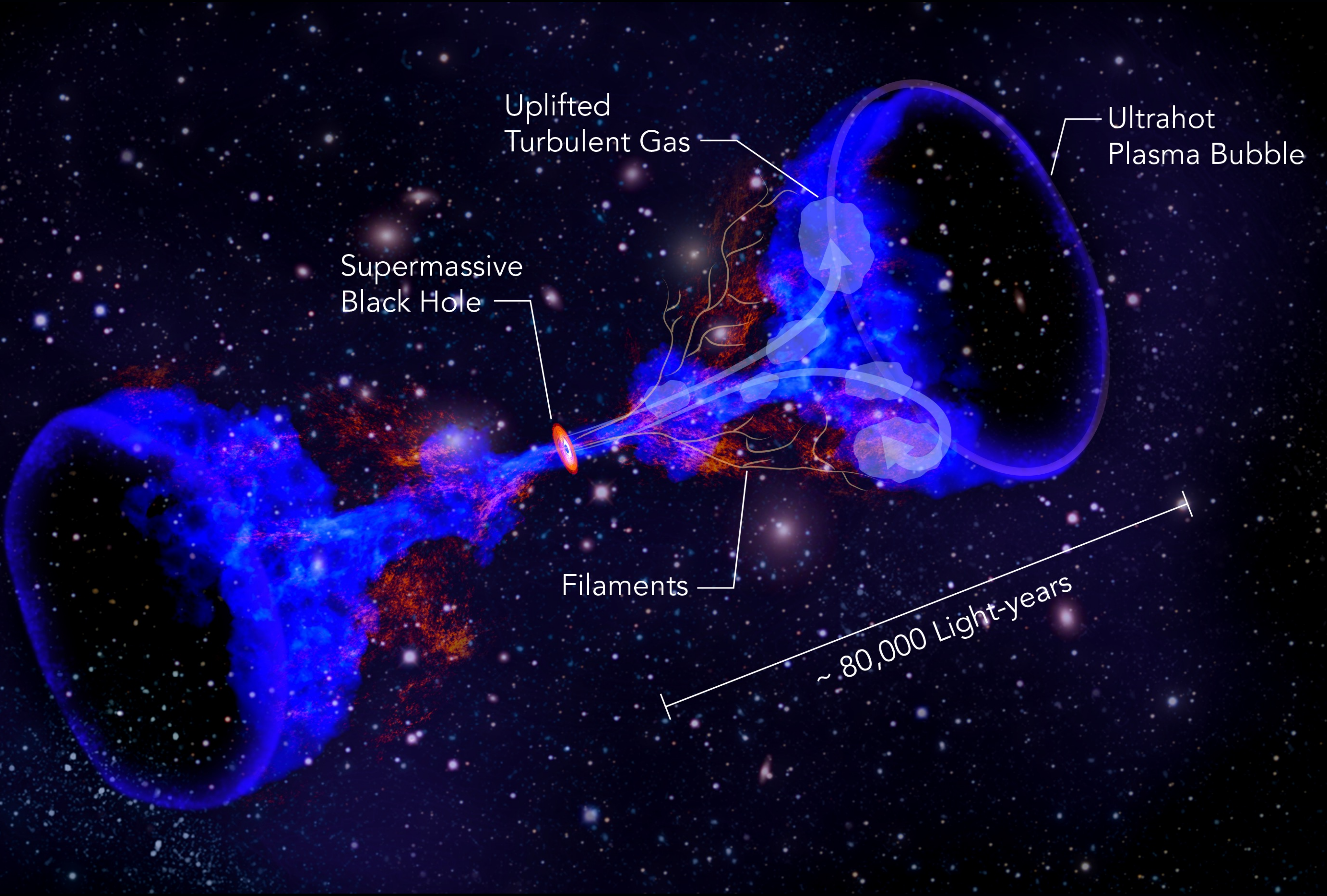


line broadening



$E_{turb}/E_{therm} \sim 2–6\%$

[On behalf of the Hitomi collaboration, PASJ 2018]


Uplifted Turbulent Gas
Ultrahot Plasma Bubble
Supermassive Black Hole
Filaments
~ 80,000 Light-years